



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

The BEAM Research Centre, School of Computing, Engineering and Built Environment, Glasgow Caledonian University, Scotland, United Kingdom

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*Correspondence:

Alejandro Gonzalez-Ollauri
alejandro.ollauri@gcu.ac.uk

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The idea of nature providing solutions to societal challenges is relatively easy to understand by the layperson. Nature-based solutions (NBS) against landslides and erosion mostly comprise plant-based interventions in which the reinforcement of slopes provided by vegetation plays a crucial role in natural hazard prevention and mitigation, and in the provision of multiple socio-ecological benefits. However, the full potential of NBS against landslides and erosion is not realised yet because a strong evidence base on their multi-functional performance is lacking, hindering the operational rigour of NBS practice and science. This knowledge gap can be addressed through the definition of repositories of key performance indicators (KPIs) and metrics, which should stem from holistic frameworks facilitating the multi-functional assessment of NBS. Herein, we propose the ‘rocket framework’ to promote the uptake of NBS against landslides and erosion through the provision of a comprehensive set of indicators which, through their appropriate selection and measurement, can contribute to build a robust evidence base on NBS performance. The ‘rocket framework’ is holistic, reproducible, dynamic, versatile, and flexible in helping define metrics for NBS actions against landslides and erosion along the NBS project timeline. The framework, resultant from an iterative research approach applied in a real-world environment, follows a hierarchical approach to deal with multiple scales and environmental contexts, and to integrate environmental, eco-engineering, and socio-ecological domains, thus establishing a balance between monitoring the engineering performance of NBS actions against landslides and erosion, and the wider provision of ecosystem functions and services. Using a case study, and following the principles of credibility, salience, legitimacy, and feasibility, we illustrate herein how the ‘rocket framework’ can be effectively employed to define a repository with over 40 performance indicators for monitoring NBS against landslides and erosion, and with over 60 metrics for establishing the context and baseline upon which the NBS are built and encourage their reproduction and upscaling.

Keywords: green infrastructure (GI), soil bio-engineering, hydro-meteorological hazards, open-air laboratories (OALs), ecosystem services, monitoring, indicators and metrics

INTRODUCTION

Nature-based Solutions (NBS) can be defined as “actions to protect, sustainably manage and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits” (Cohen-Shacham et al., 2016). They are an emerging concept referring to actions and interventions that use natural features and processes to address environmental problems at different scales. The uptake of NBS is rapidly increasing, in part because the idea of nature providing solutions is simple to understand by the layperson (Cohen-Sacham et al., 2019). However, there still are several challenges to overcome prior to realising the full potential of NBS (Nelson et al., 2020). These challenges stem from the lack of operational rigour in NBS practice and science (i.e., weak knowledge of NBS design, implementation, and evaluation), and from the lack of homogeneity between NBS concepts and frameworks, which have been generally established around eclectic disciplines such as urban sustainability, ecosystem-based and climate adaptation approaches, or conservation ecology (e.g., Raymond et al., 2017; Ruangpan et al., 2020). Still, the uncertainty associated with NBS performance is acknowledged as the greatest limitation to overcome by the existing NBS frameworks, placing monitoring activities at their core to promote the generation of a robust evidence base (Raymond et al., 2017; Woroniecki et al., 2019). Monitoring should be a transversal process across the NBS project stages, but it should also be strategically devised as a platform to gather evidence on NBS performance once specific actions have been deployed. This evidence base should convey information and confidence across the public and private sectors upon NBS performance in complex, dynamic systems, and it should consolidate the standardisation and upscaling of NBS practice, including specifications and benchmarks (e.g., Kabisch et al., 2016; Angelakoglou et al., 2019; Nelson et al., 2020).

Several frameworks have been proposed over the last few years to assess NBS projects, to define alternative courses of action, and to address the lack of evidence on NBS performance (for review, see Narayan et al., 2016; Wendling et al., 2018 or Shah et al., 2020). These frameworks agree that NBS can provide both socio-ecological and environmental benefits (and co-benefits) to a wide range of stakeholders, when deployed effectively in a given context. NBS performance has been widely proposed to be assessed using indicators from the economic, social, and environmental domains (e.g., Kabisch et al., 2016). However, most frameworks have emphasised the social domain over the ecological/environmental domain (Shah et al., 2020). This is likely because most research-oriented NBS projects have been focusing on climate adaptation and resilience within urban environments (e.g., UNaLab, Eklipse, RECONNECT). Also, the change in paradigm experienced by the field of nature conservation in the late 2000s, which evolved from focusing solely on nature to focus on people and nature, has taken NBS beyond the traditional conservation and management principles by re-focusing the debate on humans (Eggermont et al., 2015; Cohen-Sacham et al., 2019). However, NBS are not just strongly connected to socio-ecological ideas such as urban

sustainability, climate adaptation, or ecosystem-based management approaches, the concepts of green infrastructure and ecological engineering may, in fact, be closest to NBS (Eggermont et al., 2015; Fernandes and Guiomar, 2018); especially when NBS are sought to manage hydro-meteorological hazards (HMHs), such as landslides and erosion, which require the intervention and modification of the hazard-prone ecosystems to address these societal challenges (e.g., Schiechl and Stern, 1996; Morgan, 2004).

Both green infrastructure (GI) and ecological engineering strive to merge engineering principles and ecological knowledge to protect, restore, modify and/or build new ecological systems that provide services that would otherwise be provided through more conventional, ‘grey’ or ‘hybrid’ engineering (Mitsch, 2012; Anderson and Renaud, 2021). Although NBS actions belonging to the typologies of GI and ecological engineering comprise intrusive design and management of new or existing ecosystems, they can also maximise the delivery of key functions and services to human communities (e.g., Costanza et al., 1996). In fact, the consideration of ecological engineering (Eco-engineering) concepts and principles generates a unique opportunity to introduce natural dynamics into the conceptualisation of infrastructure, which is one of the key features of NBS. These aspects have been originally explored by researchers working on NBS for water treatment and for the resilience of coastal ecosystems against storm surges, flooding and erosion (e.g., Pontee et al., 2016; Thorslund et al., 2017; Reguero et al., 2018). As NBS actions based on eco-engineering follow engineering principles (i.e., ideas, rules, or concepts to be kept in mind when solving engineering problems), this opens up an exciting opportunity to utilise existing performance indicators framed in well-established and standardised engineering monitoring protocols (e.g., the Eurocodes but also e.g., Garcia-Rodriguez et al., 2019). To our knowledge, the eco-engineering performance of NBS actions against landslides and erosion has not been explicitly considered within NBS frameworks yet. Although the performance metrics for HMHs are usually strong, either in societal terms or environmental aspects (Maes et al., 2016; Woroniecki et al., 2019), they typically lack holistic perspective without including the eco-engineering domain.

Many societal challenges associated with environmental problems, and which NBS strive to address, have an engineering component and can thus be regarded as engineering problems occurring within an ecological context. The construction of wetlands to treat water at the catchment level is one example of how the combination of hydraulic engineering, water science, and plant ecology can effectively address a socio-ecological challenge such as eutrophication (e.g., Costanza et al., 1996; Thorslund et al., 2017). Wetlands and reefs can also be engineered to protect coastal ecosystems against flooding and coastal erosion (e.g., Pontee et al., 2016; Reguero et al., 2018). HMHs, such as landslides and erosion, are another example of a societal challenge that can be managed with NBS that merge civil engineering and ecological principles and knowledge (e.g., Stokes et al., 2014). Shallow landslides and erosion produce dramatic episodes of soil mass wasting and severely damage human life and

property in sloping areas worldwide. Both phenomena are mostly triggered by rainfall, which will be more frequent and intense due to climate change (Sidle and Bogaard, 2016). Yet, their impact and severity can be reduced with NBS comprising plant-based interventions in which the mechanical and hydrological reinforcement of slopes provided by vegetation plays a crucial role in the prevention, mitigation, and management of the hazards (Gonzalez-Ollauri and Mickovski, 2017a; Gonzalez-Ollauri and Mickovski, 2017b; Gonzalez-Ollauri and Mickovski, 2017c; Gonzalez-Ollauri and Mickovski, 2017d). Indicators that would confirm the effectiveness of vegetation in combatting landslides and erosion would include concepts from geotechnical engineering such as soil strength, permeability, erodibility and similar, but also concepts from environmental sciences such as land coverage or species richness. Each indicator would be a measure (metric) based on verifiable data that condenses complexity and conveys information (Haase et al., 2014). Plant-based NBS against landslides and erosion may also provide multiple socio-ecological benefits, but these will not be delivered unless the envisaged eco-engineering performance of the NBS is met. The latter stresses that the interconnectivity of context (e.g., habitat, ecosystem, landscape, etc.) in which NBS actions against landslides and erosion are deployed makes the adequate provision of eco-engineering functions essential to promote the provision of economic, social, and environmental functions and co-benefits. However, this has not been thoroughly explored in the context of NBS managing HMHs, in general, and landslides and erosion, in particular, due to the lack of holistic frameworks that foster monitoring activities through the identification of multi-functional KPIs helping to build a robust evidence base on NBS performance (Cohen-Sacham et al., 2019).

The aim of this paper is to propose a novel, holistic, and reproducible framework to define metrics and key performance indicators for monitoring NBS actions against landslides and erosion along their project timeline. The NBS project timeline incorporates all the steps undertaken pre- and post-NBS implementation to establish the project objectives, understand local conditions, conceptual and detailed design of the NBS, and choose the appropriate assessment approaches for performance, sustainability, and cost-effectiveness. The proposed framework, resultant from an iterative research approach applied in a real-world environment prone to landslides and erosion, follows a hierarchical approach to deal with multiple scales and environmental contexts, and to integrate environmental, eco-engineering, and socio-ecological domains, establishing a balance between monitoring the engineering performance of NBS actions against landslides and erosion and the wider provision of ecosystem functions and services. The proposed framework also introduces aspects to encourage the upscaling process of NBS actions against the hazards under concern. This paper is structured as follows. In the first section, we introduce the study scope and context, as well as the case study in which this paper was framed. Then, we explore the rationale behind the proposed framework, and we outline its different compartments and dimensions. Next, we present the basis for identifying metrics and KPIs using the proposed framework within the established

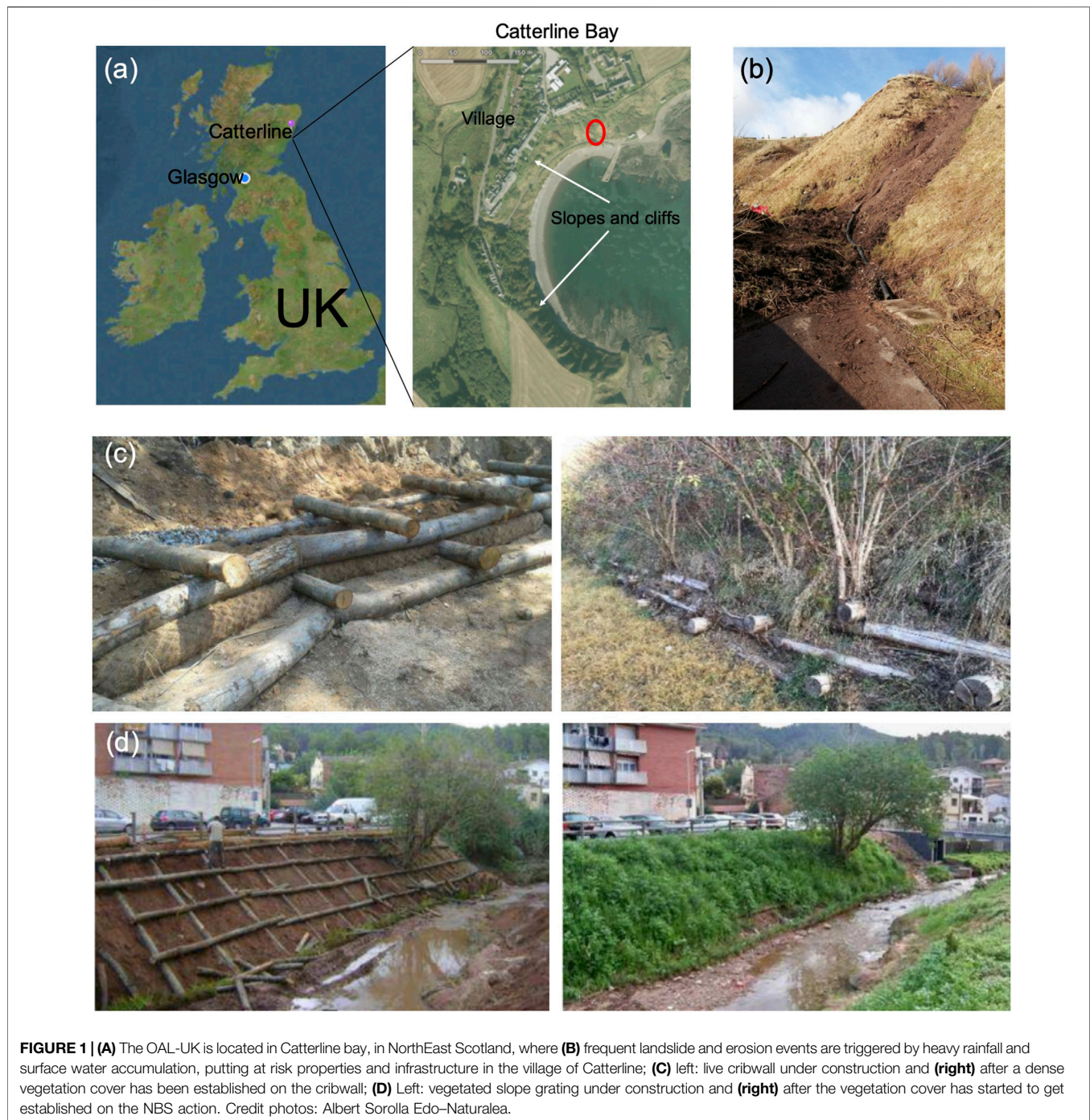
case study and with special emphasis on the monitoring stage of the NBS project. Finally, we discuss the novel aspects of the proposed framework, and its ability to build upon the NBS evidence base to encourage the uptake of NBS against landslides and erosion through facilitating and strengthening the process of monitoring NBS performance.

STUDY SCOPE, CONTEXT AND CASE STUDY

The scope of this study is to enable multidisciplinary teams of researchers, practitioners, and stakeholders to evaluate the multi-functional performance of NBS actions against landslides and erosion during the monitoring stage of the NBS project and against a pre-established baseline, providing a sound evidence base for NBS upscaling. To do so, we propose a novel framework helping to identify holistic sets of metrics and KPIs along the timeline of NBS project, providing a platform for monitoring the multi-functional performance of NBS against specific hydro-meteorological hazards (HMHs) - i.e., landslides and erosion, in a particular socio-ecological context (**Section 3**).

The proposed framework is adopted under the Open-air Laboratory established in the UK (OAL-UK) in the frame of the EU-funded Operandum project (OPEn-air laboRatories for Nature-baseD solUtions to Manage hydro-meto risks; Finer et al., 2020) to investigate how co-created NBS can help in the management of shallow landslides and erosion. OAL-UK is located in Catterline, NE Scotland, where a series of slopes and cliffs rolling into the North Sea have been subjected to severe episodes of shallow landslides and of surface and coastal erosion in the past (**Figure 1A**). The action of the sea waves during past storm surges has contributed to the destabilisation of the toe of the slopes and cliffs. However, the two major HMHs considered in this study are mostly concerned with heavy rainfall episodes and the accumulation of surface water on the slopes and cliffs forming materials (Gonzalez-Ollauri and Mickovski, 2017a). The OAL-UK benefits from a local community who are both highly informed and accepting NBS. In 2012, after a major landslide in the village damaged property and road infrastructure, local residents formed the Catterline Braes Action Group (CBAG, <https://www.cbag.org.uk/>). CBAG has implemented NBS actions prior to their involvement with the Operandum project, approaching academic and industry experts with whom to co-create NBS. Co-creation of NBS at the OAL-UK has brought technical experts together with local authorities, local communities, and other end-users to collaborate on the definition, design, implementation and monitoring of NBS, for which effective communication avenues between the team members and with the project stakeholders had to be found and established to facilitate the co-creation process.

Following the major landslide event of 2012, CBAG were struggling to overcome barriers associated with contested ownership and responsibility for the slope which was restricting potential for either a public or private funded remedial project. As an alternative, they approached an academic team of researchers from Glasgow Caledonian



University (GCU) comprising expertise in both physical and social sciences (fields spanning from environmental science, civil engineering, architecture, urban sustainability, geography, public engagement, and environmental psychology), with experience in both academia and industry. The team were interested in promoting a holistically understanding of the problem faced by the community in OAL-UK, and to propose multi-functional NBS actions, and to implement multi-dimensional, analytical approaches helping to break down the

problem and solution into their basic elements. The project reflects a collaboration between the community (through CBAG) and academia reflecting a drive towards engaged research which seeks to bridge the academia/practice/community divide by seeking to extent relevance and impact of research by seeing practitioners and the community as not only beneficiaries of its outcomes but as a key part of the process, thus promoting mutual benefit by advancing both theoretical and practical knowledge in a real-world context. Engaged research

promotes the co-production of knowledge and in this context the opportunity was presented to promote this strongly through co-creation across the project but especially during the design phase. This requires for researchers to be ‘insiders’ rather than objective researchers and for the community to act as active participants in the research process rather than the subjects. This provides the basis for an iterative research approach which is reflexive, and it is promoted by the mutual understanding and shaping of the research questions and consideration of its implications developing between the academics and the community.

The framework proposed herein (**Section 3**) represents the cumulation of the research outlined above and wider reflections from the expert team in working with NBS at OAL-UK. Since 2012, the research has followed an iterative approach to working on the OAL’s slopes alongside its community, implementing small-scale geophysical interventions against landslides and erosion alongside well-considered and informed community engagement. The research team has previously published on this iterative approach, advocating for its ability to enable decision-making, widen the evidence base for NBS design and management, and promote mediation and collaboration (Mickovski and Thomson, 2018). These benefits are critical outcomes in a project striving for co-creation, where the participation of local and regional stakeholders is vital to then enhance the design and installation of NBS through their contextual knowledge and ensuring their acceptance of research that addresses landslides and erosion while providing socio-economical co-benefits (Anderson and Renaud, 2021). Engaged research facilitates co-creation between the academics and community promoting reflexivity within an iterative approach where small interventions are designed, implemented, monitored, and evaluated before the next intervention is progressed (Creswell and Creswell, 2018). This approach allows for adaptations to be informed by the outcomes of the previous intervention; researchers with the community can establish what worked, what didn’t work, and make informed decisions on how to approach and improve the research based on these. Although iterative approaches are associated predominantly with the social sciences (Creswell and Creswell, 2018; Aspers and Corte, 2019), the authors have experienced success in the use of small, incremental interventions within the bio-geophysical landscape, finding it to have aided in the development of a deeper understanding of the physical characteristics of the OAL and therefore to apply NBS against landslides and erosion proactively (i.e., identify and prevent), rather than reactively (Mickovski and Thomson, 2018). For the socio-ecological aspects, an iterative approach can help ensure that the needs, priorities and expectations of the local stakeholders occupy a central place in the design and implementation of NBS. In a linear approach, stakeholders may only be significantly involved at the design and evaluation stages, limiting the opportunity for both of them to give input and for the research team to take this input into account. This provides a separation between the academic and community during the research, whereas an iterative approach provides local stakeholders with multiple opportunities to steer the direction of the interventions, as well as having the chance to

see interventions succeed; this need for proof has been shown to be influential over acceptance and willingness to participate in NBS co-creation (Mickovski and Thomson, 2018; Anderson et al., 2021; Anderson and Renaud, 2021) as it builds trust in the NBS itself and in the research team. Therefore, the provision of “proof” of a successful intervention within an iterative approach benefits later cycles of co-creation of NBS interventions and actions against landslides and erosion.

The NBS actions against landslides and erosion identified and co-created for OAL-UK belong to the ‘green infrastructure’ typology (Eggermont et al., 2015) and in the third category of NBS proposed in the IUCN’s NBS framework (i.e. infrastructure; Cohen-Sacham et al., 2019), and they follow the principles of ground/soil bioengineering techniques (Schiechl and Stern, 1996). Herein, we are focusing on two specific NBS actions against shallow landslides and erosion control - i.e., vegetated cribwall and live slope grating, (**Figures 1C,D**). Live cribwalls are retention walls built with timber logs which are deployed forming a crib that is then anchored to the slope and ground (**Figure 1C**). The crib is subsequently backfilled with earth materials and local vegetation (e.g., tree cuttings, saplings) is planted on the upper and external faces of the cribwall to provide long-term mechanical and hydrological stability (Gonzalez-Ollauri and Mickovski, 2017a). The slope above the cribwall is generally reworked and flattened (Gray and Sotir, 1996) and covered with vegetation. Slope gratings are slope ‘skins’ built with timber logs that form a lattice that is anchored into the slope (**Figure 1D**). The cells of the lattice are filled with earth materials and local vegetation is planted on the surface.

FRAMEWORK DESCRIPTION, DIMENSIONS AND COMPONENTS

We propose the ‘rocket framework’ (**Figure 2**) to help identify a holistic set of metrics and key performance indicators (KPIs) along the timeline of NBS projects seeking to manage and/or address context-specific hazards of landslides and erosion. The ‘rocket framework’ is a systems-based, heuristic framework (e.g., Eakin et al., 2017) that integrates multiple levels and domains resulting from undertaking a thorough system analysis (e.g., Calliari et al., 2019) by which we broke down ‘analytically’ the components and stages of projects concerning NBS against landslides and erosion. Each framework level corresponds to a stage along the NBS project timeline. Within each level of the framework, multiple, multi-dimensional compartments are integrated to help portray processes relevant for selecting, deploying, monitoring, and upscaling specific NBS actions against the HMs of concern. The different dimensions of each compartment within the framework arise from the current definitions of NBS that feature in the peer-reviewed literature (e.g., Raymond et al., 2017; Ruangpan et al., 2020). As a result, each framework compartment unfolds into environmental, social, and economic domains, which were re-arranged into different dimensions depending on the project stage (**Figure 2**). The ‘rocket framework’ also contemplates the appearance of a new, emerging context resulting from deploying

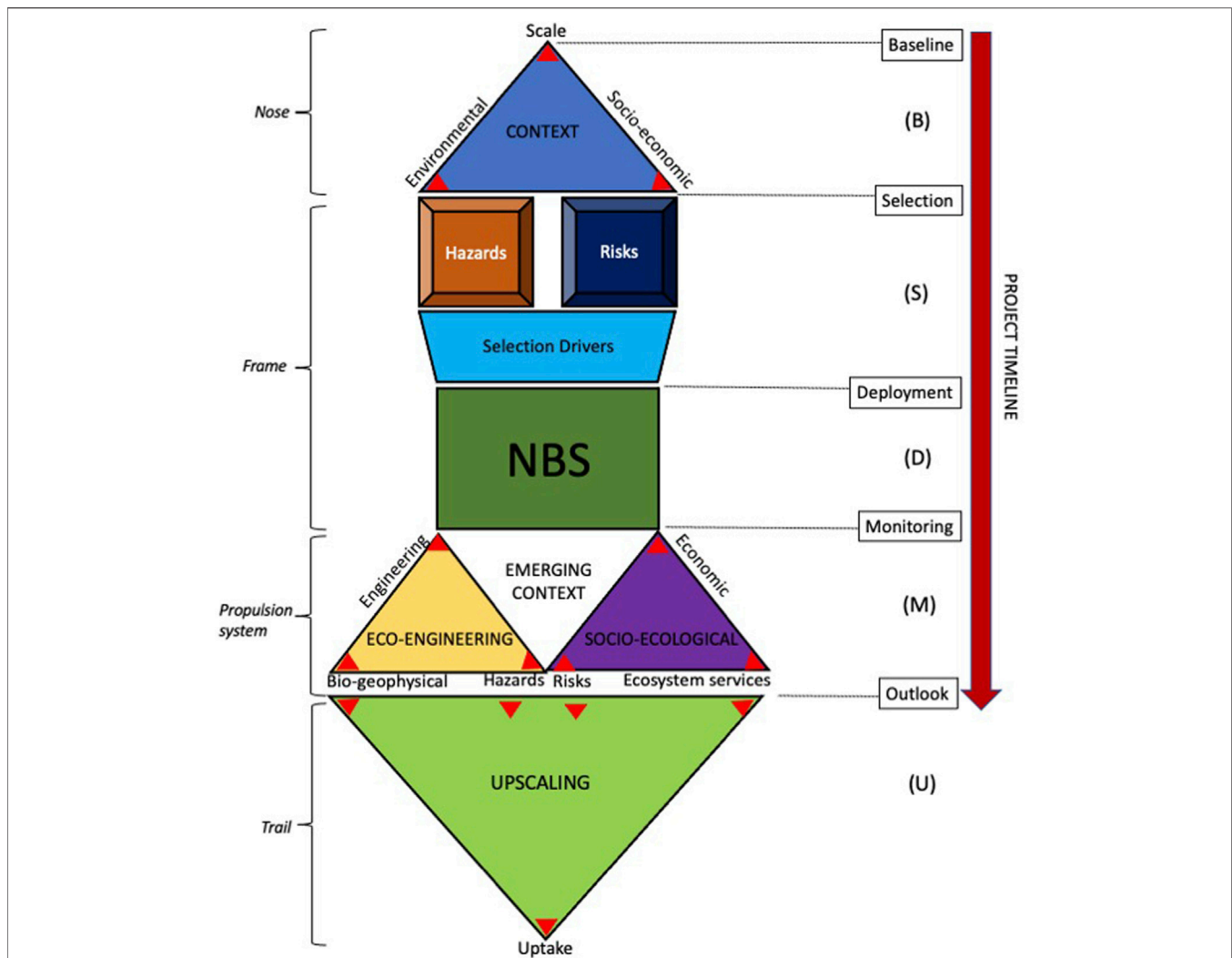


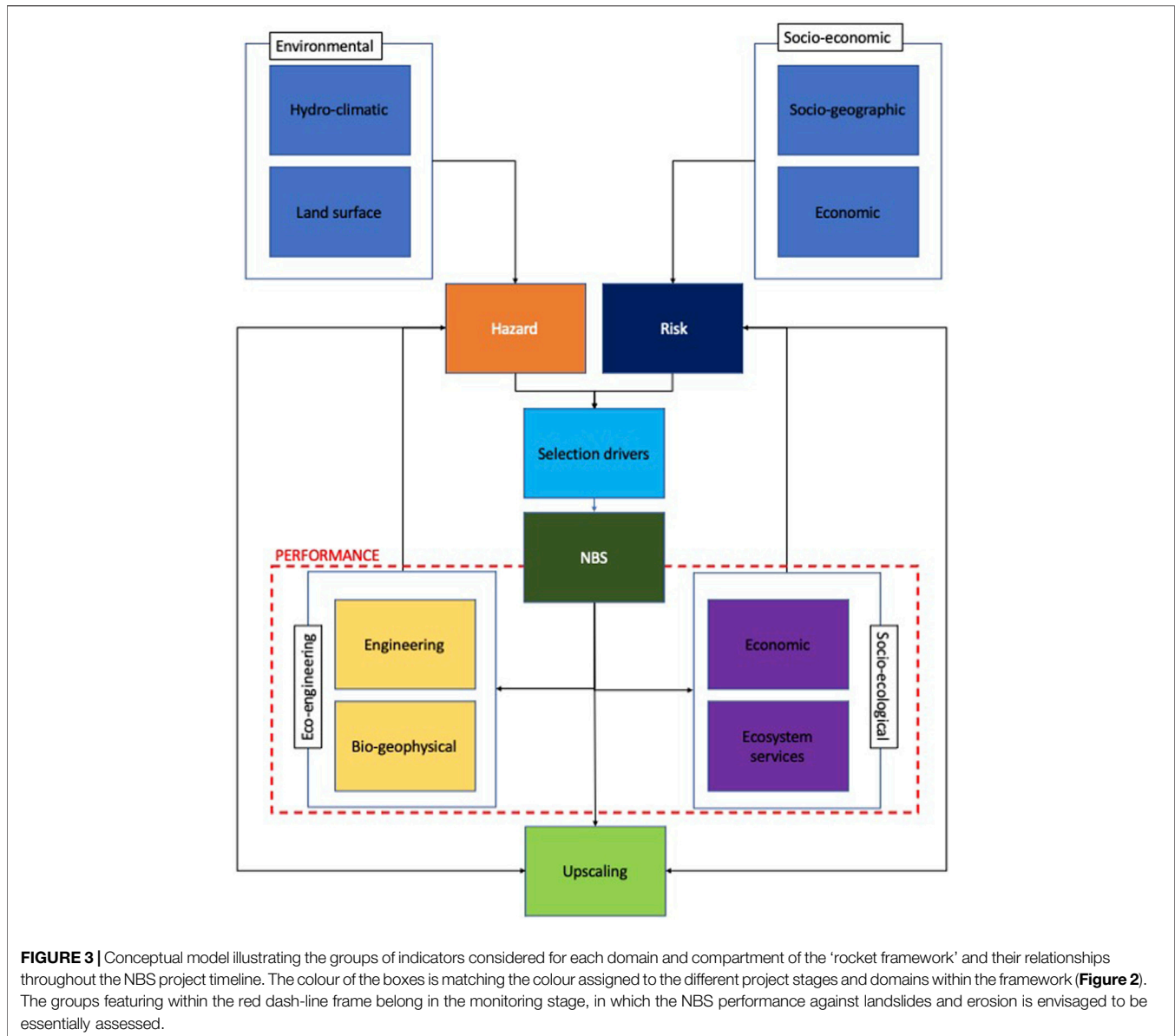
FIGURE 2 | The ‘rocket framework’ strives to facilitate the operationalisation of NBS actions against landslides and erosion by helping to articulate the thinking process involved in the identification of multi-functional key performance indicators at different stages of the NBS project -i.e., baseline establishment (B), NBS selection (S), deployment (D), and monitoring (M), which is the stage in which NBS performance against landslides and erosion is envisaged to be essentially assessed. The vision of the ‘rocket framework’ is to ‘uplift’ the acceptance and reproduction of NBS actions through facilitating the provision of a strong evidence base on their performance. The ‘rocket framework’ is inspired in the illustration of spatial rockets (e.g., <https://www.grc.nasa.gov/www/k-12/rocket/rockpart.html>) to make it easy to memorise the dimensions and compartments that should be considered in the process of monitoring NBS against landslides and erosion. The capital letters in brackets help identify the project stage for the indicators provided in **Table 1** and **Supplementary Material**.

NBS actions against landslides and erosion at a site which, through the correct functioning of the NBS, will be environmentally and socio-ecologically transformed and less prone to adverse natural disturbance and risks brought by landslides and erosion (Gonzalez-Ollauri and Mickovski, 2017b). A conceptual model illustrating the relationship between the multiple framework components is provided in **Figure 3**, which was used as the basis to identify groups of indicators (**Table 1** also see **Supplementary Material** for full description of metrics and their relationship with NBS performance). Although the main focus of this study rests in the monitoring stage of the project, which is the *propulsion system* of the “rocket framework” (**Figures 2, 3; Table 1**), we are also providing a comprehensive set of metrics portraying the baseline,

selection, deployment and upscaling of NBS against landslides and erosion (**Supplementary Material**). We believe that the latter metrics can also assist in the monitoring process to cast light on the performance of NBS.

Stage I: Project Baseline

The *nose* of the ‘rocket framework’ provides information about the context in which a given hazard and its related risks take place. This compartment belongs to the baseline stage of the NBS project, as it seeks to provide basic information on which the identification and selection of NBS actions are based upon. In addition, it strives to furnish basic information against which the performance of the selected NBS will be evaluated during the monitoring stage (**Figure 3; Table 1**). The context is portrayed by



the scale, and by its environmental and socio-economic dimensions. The environmental dimension of the context comprises attributes describing the hydro-climatic and land surface features of a site (e.g., air temperature, precipitation rate, topography, soil texture, land cover, etc; **Supplementary Material**). The environmental dimension also establishes the likelihood and recurrence of landslides and erosion at a given site -i.e., the problem for which NBS actions are designed in the context of this study. The socio-economic dimension of the context comprises social, economic, and cultural features of a particular site and is concerned with aspects such as population density, population demographics, economic activity, and cultural heritage (**Supplementary Material**). The socio-economic dimension establishes the boundaries within which citizen engagement and participation in NBS projects occur. The identification and engagement of stakeholders within the context

is crucial to the function and success of NBS co-creation activities (Durham et al., 2014; Anderson et al., 2021). Here, a stakeholder mapping processes is established/envisaged to gain understanding of the interested groups: who they are, what their needs, expectations or priorities are, the extent to which their support is essential to aid project success, and the levels of interest and investment of certain parties (Durham et al., 2014; Talò, 2017). Through the understanding of these factors, effective stakeholder engagement strategies can be developed to ensure that the correct citizen groups are involved in the co-creation process at the correct time, and in an appropriate manner (Durham et al., 2014). Moreover, the socio-economic dimension determines the perceived virulence of landslides and erosion and the need for action against them: that is, the risk seen to be posed by these natural hazards. Studies have shown that risk is often a matter of perception, i.e. people who are

TABLE 1 | Indicators repository originating from the 'rocket framework' (Figures 2, 3) to monitor the performance of plant-based NBS against landslides and erosion at the monitoring stage (M).

Project stage	Domain	Compartment	Indicator number	Indicator ^a	Metric	Measurement unit	References	
MONITORING (M)	Eco-engineering performance	Engineering	M1	Resistance to sliding	Active earth force Shear resistance	N m ⁻¹ N m ⁻¹	EN-1997-1	
			M2	Resistance to overturning	Active earth force Overturning resistance	N m ⁻¹ N m ⁻¹	EN-1997-1	
			M3	Resistance to shear failure	Wall-face contribution to stability	N m ⁻¹	EN-1997-1	
			M4	Resistance to bending	Bending stiffness	N m ⁻¹	EN-1997-1	
			M5	Pull-out resistance	Pull-out force	N m ⁻¹	BS EN 1383:2016	
			M6	Resilience and durability of the structure	Wood decay		EN 1995-1-1 Tardio and Mickovski (2016)	
		Bio-geophysical	M7	Plant cover	Plant counts Crown area	No m ²	m ⁻² m ⁻²	Muukkonen and Makipaa (2006)
			M8	Plant growth	Plant biomass	kg	m ⁻²	Keeton (2008)
					Canopy cover fraction	%		Gonzalez-Ollauri and Mickovski (2017d)
					Plant mortality	No		
					Height	m		Passioura (2002)
			M9	Plant diversity	Basal area	m ²		Gonzalez-Ollauri et al. (2020a)
					Crown area	m ²		
					Leaf area index	m ² m ⁻²		
			M10	Rainfall partitioning	Canopy cover fraction	%		
					Shannon index	-		Gonzalez-Ollauri and Mickovski (2017d)
					Rainfall interception	mm		Zimmermann and Zimmermann (2014)
			M11	Raindrops impact energy	Stemflow	mm		Gonzalez-Ollauri and Mickovski (2017a)
Dripfall	mm				Gonzalez-Ollauri et al. (2020b)			
M12	Root profile	Root area ratio	%		Vaezi et al. (2017) Nanko et al. (2004)			
M13	Root reinforcement	Root pull-out force	MPa		Gonzalez-Ollauri and Mickovski (2016)			
		Root tensile strength	MPa		Gonzalez-Ollauri and Mickovski (2017b)			
M14	Soil wetness	Apparent root cohesion	kPa		Schwarz et al. (2010)			
		Volumetric soil moisture content	%		Lu and Godt (2010)			
		Matric suction	kPa		Basist et al. (2006)			
M15	Soil temperature	Piezometric level	m					
		Soil wetness index						
M16	Soil respiration	CO ₂ efflux	μmol m ⁻² s ⁻¹		Alvarez-Uria and Körner, (2007) Meyer et al. (2018) Gonzalez-Ollauri et al. (2020a)			
M17	Soil fauna	Soil fauna index	No		Raich and Tufekcioglu, (2000)			
		Species counts			Yan et al. (2012)			
M18	Evapotranspiration	Shannon Index			Briones, (2014)			

(Continued on following page)

TABLE 1 | (Continued) Indicators repository originating from the 'rocket framework' (Figures 2, 3) to monitor the performance of plant-based NBS against landslides and erosion at the monitoring stage (M).

Project stage	Domain	Compartment	Indicator number	Indicator ^a	Metric	Measurement unit	References
			M19	Belowground preferential flow	Potential evapotranspiration rate Bypass flow rate	mm s	Allen et al. (1998) Feng et al. (2020)
	Socio-ecological	Economic	M20	Energy use	Energy performance index (EPI)	kWh m ⁻²	Clothier et al. (2008) Zhang et al. (2018) Gonzalez-Ollauri et al. (2020b) UK Government – Department of Communities and Local Government, (2017) Bakar et al. (2015)
			M21	Water consumption	Water consumption Water exploitation index (WEI+)	m ³ m ⁻² %	Thomback et al. (2015) EEA, (2021)
			M22	Waste generation		Kg m ⁻²	Bakshan et al. (2015)
			M23	Whole life cost		£	
			M24	Operational cost		£	
			M25	Value of provided resources		£	Keesstra et al. (2018)
			M26	Employment generation		No. %	Wild et al. (2017)
			M27	Quality of construction	CONQUAS score	%	Low and Ong, (2014)
		Ecosystem services and co-benefits	M28	Accessibility of natural space		m2%	Frumkin et al. (2017)
			M29	Aesthetic perception		Qlt	Daniel, (2001)
			M30	Recreation	Organised recreation groups Informal recreation activities	No Qlt	Sutton-Grier et al. (2015)
			M31	Stakeholder engagement with co-creation		No	Soini et al. (2020)
			M32	Changes in well-being		Qlt	Van den Bosch and Sang, (2017)
			M33	Tourism generation		Qlt	Sutton-Grier et al. (2015)
			M34	Cultural heritage		m ²	Sutton-Grier et al. (2015)
			M35	Materials provided		No	de Groot et al. (2002)
			M36	Habitat provision		No m ²	Sutton-Grier et al. (2015)
			M37	Habitat support		No m ²	Sutton-Grier et al. (2015)
			M38	Air quality regulation	Daily Air Quality Index	Qlt	Defra, (2021)
			M39	Water cycle regulation	soil water mass balance		Voltz et al. (2018)
			M40	Carbon cycle regulation	Soil organic carbon Woodland carbon code	mg kg ⁻¹ tCO ₂ ha ⁻¹	Harden et al. (2018) Forestry Commission, (2018)
			M41	Climate regulation	Heat regulation index Moisture regulation index		West et al. (2011)
			M42	Landscape quality	Landscape quality indicator		Daniel, (2001) Sowińska-Świerkosz and Michalik-Śnieżek, (2020)

^aFor full description of the metric and its relationship with NBS performance see Supplementary Material. Qlt., qualitative; No, number or counts.

exposed to the same hazard may not perceive their own or their community's level of risk equally (De Dominicis et al., 2015; Rufat et al., 2015). Risk perception has been shown to be influenced by emotions (e.g., fear), prior experience of hazards, trust in authorities and/or solutions, and place attachment (Keller et al., 2012; Wachinger et al., 2013; De Dominicis et al., 2015; Rufat et al., 2015).

The scale of the context can be both spatial and temporal. The consideration of the scale is crucial for establishing boundaries around a given context and to determine the size of the NBS action—e.g., landscape, catchment, stand, or individual intervention scale (e.g., Bock et al., 2005). Some HMHs can only be perceived within a given spatial and temporal scale (e.g., landslides—landscape scale and slow; erosion—both landscape and catchment scales, and both slow and fast; flooding—catchment scale and fast), and frequently recurring problems or hazards may require greater efforts and NBS actions that are more flexible and resilient to disturbance. It is also essential to consider both the temporal and spatial scales in the context of socio-economic considerations, as the scales will be a factor in the priorities and perceptions of stakeholders. Careful planning with the context's scale in mind is needed to ensure the connectivity between multiple NBS actions and the environment as well as the communities in which they are embedded, so they can perform effectively to deliver the functions for which they were designed (Calliari et al., 2019).

Stage II: Nature-based Solutions Action Selection

The *frame* of the 'rocket framework' comprises the selection and deployment (Section 3.3) stages of the NBS project (Figure 2). The selection stage firstly involves the characterisation of the hazard (i.e., landslide and/or erosion) and its associated risks, using metrics belonging to the environmental/geo-physical and socio-economic dimensions, respectively, which stem from the context compartment described above (Figures 2, 3; Supplementary Material). In a co-creation approach, the involvement of stakeholders from the outset is a crucial feature of the selection stage. Following stakeholder mapping, the identified stakeholders make contributions to the definition and characterisation of the hazard, through providing their perception of it through informal conversation, public meetings, and focus groups. The selection stage should indeed reflect the on-site conditions and bio-geophysical evidence but also consider the priorities of the stakeholders, who must feel heard and represented to achieve successful co-creation (Talò, 2017; Anderson et al., 2021). There is a distinction to be made between hazard and risk: on one hand, the hazard under concern should be characterised in the light of direct, site evidence where possible (e.g. slow-moving hazards such as landslides) but, most likely, this is described in terms of its likelihood and recurrence using predictive and probability models (e.g., Gonzalez-Ollauri and Mickovski, 2017c). On the other hand, the perceived risk can be evaluated after the hazard's likelihood is known, and specific risk assessment frameworks and models can be used for this purpose (Shah et al., 2020). These normally involve using

socio-economic variables (e.g., scale of property damage; scale of impact on economic activity; damage to cultural heritage; knowledge of hazard cause and prevention **Supplementary Material**) that are understood through analysis of risk perception of stakeholders (e.g., Shah et al., 2020). The characterisation of hazards and risks will inform the NBS selection process, and we suggest re-evaluating these two compartments at the monitoring stage in the frame of the emerging context (Figures 2, 3; Table 1) to acknowledge whether the NBS actions are contributing to mitigate, manage, or reduce the hazard and the risks for which they were planned, and so NBS upscaling can be promoted (Cohen-Sacham et al., 2019).

The NBS selection process is characterised in the proposed framework (Figure 2) through a series of selection drivers associated to a co-creation process (**Supplementary Material**; Soini et al., 2020), which involves the participation of stakeholders mapped within the baseline definition stage. The selection drivers also belong in the environmental/bio-geophysical, and socio-economic dimensions, feeding a decision-making process in which NBS actions against landslides and erosion are first proposed by experts, they are then presented to participating stakeholders and assessed in terms of their feasibility and perception. This process involves a dialogue between those with technical expertise and the stakeholders, where a consensus is reached on NBS that are both effective against landslides and erosion in terms of bio-geophysical characteristics, and appropriate to meet the needs, expectations or priorities of the stakeholders (e.g., aesthetic qualities, cost, reduction of perceived risk). Once solutions are agreed upon the process moves to designing and deploying (or co-deploying) the selected NBS actions.

Stage III: Nature-based Solutions Deployment

The 'rocket framework' facilitates the strategic deployment of NBS actions against landslides and erosion at spatial locations where the hazards and risks have been identified, and where the implementation of a NBS action is feasible from the engineering, environmental and socio-economic viewpoint. The deployment stage of the NBS project is envisaged as an opportunity to promote further the participation of stakeholders (i.e., co-deployment), to exchange knowledge, and to build capacity in NBS science and practice across the private and public sectors. The NBSs identified herein (Section 2) require low machinery input and the utilisation of locally available resources, such as plant cuttings, timber logs, and earth materials, making it easier to engage with local communities (i.e., end-users) during the deployment process (e.g., <http://www.efib.org/activities/>).

Stage IV: Nature-based Solutions Performance Monitoring

The *propulsion system* of the 'rocket framework' comprises the monitoring stage of the NBS project (Figures 2, 3). This stage strives to provide information about the performance of the NBS actions against landslides and erosion using KPIs from

the eco-engineering and socio-ecological compartments (**Figures 2, 3; Table 1**), to characterise the emerging context resulting from deploying NBS actions, and to ‘uplift’ the uptake of NBS against these HMHs across the private and public sectors through the provision of a robust evidence base. We understand that effective engagement with stakeholders together with the provision of co-benefits (e.g., ecosystem services, resilience towards further natural stress and disturbance, additional economic income; Raymond et al., 2017) are central in NBS projects, as these will foster the positive perception, acceptance, and upscaling of NBS (Cohen-Sacham et al., 2019). However, we wish to stress the importance of considering eco-engineering performance in NBS projects against landslides and erosion, as the socio-ecological performance of NBS actions will not be fulfilled as expected unless the NBS actions are delivering the ecological and engineering functions for which they were designed, thus managing and mitigating the HMHs under concern effectively and sustainably, and delivering an emergent, hazard and risk-free context.

The eco-engineering performance is herein concerned with the provision of tangible functions seeking to manage or mitigate landslide and erosion hazards. We believe that these functions can be quantified using engineering principles, which need input from the surrounding bio-geophysical environment. Moreover, the NBS action, understood here as a green infrastructure intervention, will transform the bio-geophysical context in which it is established, in turn regulating the engineering function of the NBS actions (e.g., Stokes et al., 2014). Consequently, the eco-engineering compartment comprises three dimensions: 1) engineering: evaluation of the engineering stability and resilience of NBS actions; 2) bio-geophysical: evaluation of the tangible changes triggered by NBS actions in the habitat, ecosystem and/or landscape in which they are established, and which are intrinsically related to the engineering functions the NBS actions perform; and 3) hazards: assessment of the likelihood and recurrence of landslides and erosion in the emerging context in which the NBS actions have been deployed.

The socio-ecological performance is chiefly concerned with the provision of additional goods and services to human communities (i.e., ecosystem services and co-benefits), rather than the provision of functions specifically related to managing landslides and erosion. These could be relating to an increase in access to the natural environment which, studies have shown, have positive impacts on physical and mental health (e.g., Frumkin et al., 2017). Increasing the provision of nature can also have economic benefits such as increasing the value of surrounding properties or increasing touristic income to an area (e.g., Trojanek et al., 2018; **Table 1**). Assessment approaches commonly used for quantifying ecosystem services bundles and synergies can be considered to assess co-benefits (e.g., de Groot et al., 2002; Gonzalez-Ollauri and Mickovski, 2017e). However, it is worth noting that co-benefits provided by a given NBS action can overlap with the eco-engineering functions, strengthening the interconnectivity of the elements of the emerging context following NBS implementation (**Figure 2**). Negative services or

disservices should be considered, too (i.e., negative and unexpected impacts). For example, the vegetation cover established on the NBS can lead to the production of pollen, which may have a negative impact on public health. Additionally, increased touristic interest can become undesirable if the infrastructure services are not there to adequately support it (e.g., road capacity, parking, waste services). Care must also be taken in the selection of plant and seeds, to avoid the introduction of flora or fauna that would prove invasive to native species.

The proposed framework also considers economic and life-cycle aspects within the socio-ecological compartment (**Figures 2, 3**). These aspects relate to the costs (time and money/carbon) and resources needed to conceptualise, procure, design, construct, operate/maintain/monitor and, in some cases, decommission the NBS (**Table 1**). Life-cycle assessment/analysis concepts (Klopffer and Grahl, 2014)) can be used to forecast the energy and material fluxes over the life cycle of the NBS and monetise them to the limits of their applicability (Ayres, 1995). In addition, the socio-ecological compartment also includes assessment of the risks under the conditions of the new emerging context, which can be re-evaluated following the same approaches used in earlier stages of the NBS project (**Figures 2, 3**).

Stage V: Upscaling

The *trail* of the ‘rocket framework’ comprises the NBS upscaling stage, which is foreseen to be supported by the information generated in the monitoring stage (**Figures 2, 3; Table 1**). The tip of the upscaling compartment is featured by the uptake of NBS actions by decision-makers and the public (Sarabi et al., 2020). Thus, the upscaling compartment contains a heterogeneous array of indicators focused on acceptability, perception, and well-being provided by NBS actions which could be framed as ecosystem services and/or co-benefits, but also, of bio-geophysical indicators transformed or regulated by the NBS actions and which can contribute to the reproducibility and future monitoring assessment of the upscaled NBS actions elsewhere and over time (**Supplementary Material**).

METRICS AND KEY PERFORMANCE INDICATORS FOR NATURE-BASED SOLUTIONS AGAINST LANDSLIDES AND EROSION

Definition, Identification, and Selection of Metrics and Key Performance Indicators

An indicator can be defined as a measure (metric) based on verifiable data that condenses complexity and conveys information (Haase et al., 2014). Herein, we refer to key performance indicators (KPI) to pool metrics able to provide information related to the performance of NBS actions against landslides and erosion during the monitoring stage of an NBS project. We also use the term ‘key’ because it is assumed that the indicator has undergone a selection process and, thus, the most representative metric for a given function/process has been selected under the existing constraints of the NBS project. For

the other project stages (**Figure 2**), we use the terms metric or indicator instead of KPI, even though the identified metrics have also undergone a selection process, which should be refined further by future users of the framework on the basis of project context, scale, scope and capacity. Generally, there are multiple metrics available for one indicator or performance goal (**Table 1** and **Supplementary Material**), so metrics should be selected from the proposed pool in the light of the available skills and resources, scale of analysis, and/or feasibility to take measurements of the selected metric (Raymond et al., 2017). However, whichever metric is chosen, it should meet the principles of credibility, salience, legitimacy and feasibility (Cash et al., 2020). By following these principles for selecting metrics and indicators, a minimum level of comparability will be ensured between NBS and case studies, thus contributing to build upon the NBS evidence base (Kabisch et al., 2016). Yet, it is understandable and expected that the indicators will change with regards to context and scale (Raymond et al., 2017), as indicated above.

A wide range of metrics and indicators should be identified to reflect the multifunctionality of NBS actions against landslides and erosion (Calliari et al., 2019; **Figure 3** and **Table 1**). The proposed 'rocket framework' (**Figure 2**) provides, through its multiple compartments and dimensions (and their connections; **Figure 3**), a good basis to capture the multiple functions defining holistically the performance of NBS actions against the above-mentioned HMHs. To this end, each dimension in the framework can be understood as a gap that must be filled up with measurements to achieve a good level of insight into NBS performance against landslides and erosion during the monitoring stage (**Figure 3**; **Table 1**; also see **Supplementary Material** for full description of metrics and KPIs). Though the performance of the NBS should be fundamentally assessed during the monitoring stage, the project stages prior to monitoring will set a context and a baseline for testing the NBS performance.

In this study, the multidisciplinary team of researchers followed an analytical, brainstorming approach during a series of five meetings (i.e., one per NBS project stage) by which the problems and elements of the identified NBS actions (**Section 2**) were broken down into representative drivers, components, and expected outcomes, and by following the structure provided by the 'rocket framework' (**Figures 2, 3**). This brainstorming approach, which sought co-creation between academic researchers of multiple disciplines, enabled the team's participation and access to the process, discourse and mutual understanding to reach consensual outcomes. In addition, engaging the OAL-UK's community in this process was necessary where relevant to ensure that the emerging outcomes reflect the context and preferences were gained from their local experience. It was also assumed that the identified NBS actions should manage landslides and erosion through the regulation of their drivers and components (e.g., Raymond et al., 2017). The variables and factors that are expected to be regulated by NBS actions against landslides and erosion will need measurement through monitoring to convey information on their performance, for which baseline information related to the context is also essential, as indicated above. Next, we carried out a quick scoping review of the peer-reviewed scientific and grey literature (e.g., Collins et al., 2015), which was not intended

to be comprehensive but informative enough to identify metrics for each indicator. The scoping consisted in three stages (Raymond et al., 2017): 1) structured search of the peer-review scientific, including textbooks, and grey literature, including standards, using Google Scholar, 2) selection of literature resources based on relevance to problem and/or specific indicator, and 3) narrative synthesis of the selected scientific literature. In total, 99 documents were read to at least the abstract level (**Table 1** and **Supplementary Material**).

Context Indicators

Context indicators provide information about the baseline on which NBS actions against landslides and erosion are established (**Supplementary Material**; **Figure 2**). The problem of landslides and erosion can be described on the basis of context indicators referring to the scale and environmental factors underpinning the problem. The extent and risks associated to it can be characterised using socio-economic attributes (**Supplementary Material**). The context indicators are not classified as KPIs herein, as they are not explicitly referring to the NBS performance. Yet, NBS performance should be assessed based on its context or baseline.

Following the three dimensions established in the context compartment of the 'rocket framework' (**Figure 2**), and following the analytical, brainstorming approach outlined above, we identified a series of features that enabled us to describe the context and establish a baseline for our case study (**Section 2**). An extensive but not exhaustive list of context indicators and related metrics is shown in **Supplementary Material**. Regarding the scale, both space and time were considered in order to establish a baseline related to the geographic size of the landslides and erosion events occurring at OAL-UK, which was set at the landscape scale, as well as its frequency and recurrence (Mickovski and Thomson, 2018). Regarding the environmental dimension, hydro-climatic and land surface features were considered to be relevant for understanding and predicting landslides and erosion events (**Figure 3**; **Table 1**; Gonzalez-Ollauri and Mickovski 2016; Gonzalez-Ollauri and Mickovski, 2017c). The socio-economic dimension was divided into socio-geographic and economic domains (**Figure 3**; **Supplementary Material**). The metrics within socio-economic context are primarily described by secondary source data from the Scottish Index of Multiple Deprivation (SIMD) 2016 and Scottish Census 2011, both of which also establish the spatial scale as data output zones (**Supplementary Material**). The SIMD and Census gather socio-economic data at a national level every 4 and 10 years respectively, allowing local, regional and national comparisons to be drawn. The most relevant dimensions were deemed to be population size and demographics (i.e., gender, age, education and employment levels) in addition to geographic dimensions such as access to and services and infrastructure.

Indicators for the Hazards, Risks, and Nature-based Solutions Selection and Deployment

Hazard indicators are those conveying information about the occurrence of a landslide and/or erosion event *ex-ante* (i.e., before

the NBS action has been deployed) and *ex-post* (i.e., after the NBS has been deployed). Hazard indicators were split into predictive and empirical (**Figure 3; Supplementary Material**). Predictive hazard indicators strive to provide robust information about the likelihood and recurrence of the landslide and/or erosion event. These indicators are data- and computationally-intensive, as their calculation depends on the availability of relevant time series, as well as to data from a comprehensive set of variables, which are normally related to the bio-geophysical context. These indicators can be based on statistical modelling (e.g., Gonzalez-Ollauri and Mickovski, 2017c), which can evaluate the probability of a landslide and/or erosion event on the basis of a baseline feature, such as rainfall intensity or runoff, or they can be based on more elaborated, process-based indices combining multiple variables from the context, such as the soil loss equation for computing erosivity (Benavidez et al., 2018), or the limit equilibrium model for computing slope stability (Lu and Godt, 2013). Empirical hazard indicators provide first-hand evidence about a particular hazard and they must be collected on site or using primary data. For the case of landslides and erosion, it is convenient to follow principles and protocols from geotechnical engineering (e.g., AGS, 2007) and edaphology (e.g., Morgan, 2004). Examples of empirical indicators for these two hazards are those providing information related to soil mass movement and deformation or to land exposure (**Supplementary Material**).

Risk indicators are defined by not just the context and hazard that they are relating to, but also by the perception of the stakeholders who experience the hazard (**Figure 3**). Consequently, risk indicators were split into those relating to 'damage' and those relating to 'risk perception' (**Supplementary Material**; also see **Supplementary Material** for full description of selection and deployment metrics). As previously discussed, factors such as prior experience of hazards, or knowledge of (and preparedness to respond to) a hazard can increase or reduce the level of risk a population perceives themselves to be at (De Dominicis et al., 2015; Shah et al., 2020). Risk indicators are therefore both objective—in that there is often a measurably likelihood that a hazard will place a population under a certain risk—and subjective, as a population can perceive a risk as less when they are accepting, aware or prepared for it (e.g., De Dominicis et al., 2015). We followed herein the approach proposed in Shah et al. (2020), where the risks within NBS sites are broadly categorised by four factors: 1) ecosystem susceptibility—indicators can be biodiversity levels, rate of shoreline erosion; 2) ecosystem robustness—indicators can be presence of environmental protection policies, hardness of agriculture and biodiversity; 3) social susceptibility—indicators can be diversity in sources of economic income; presence of natural and cultural heritage protection; property values and insurance costs; and 4) coping and adaptive capacity—indicators can be presence of protective measures against hazard; monitoring systems, community action plan against hazard.

NBS selection indicators are informed both by the bio-geophysical characteristics of the site, and by the needs, expectations and priorities that emerge from stakeholder

mapping and engagement processes (**Figures 2, 3**). NBS selection indicators emerging from stakeholders can be aesthetic perception (e.g., increasing or preserving the natural aesthetic of their community), installation and maintenance costs, or speed and visibility of results. Consequently, we divided the selection drivers for NBS against landslides and erosion into four groups: 1) hazard-specific, 2) site-specific, 3) economic, and 4) socio-ecological (**Supplementary Material; Figure 3**). Similarly, we split NBS deployment indicators into socio-ecological, engineering, and bio-geophysical domains (**Supplementary Material; Figure 3**) with the aim to provide an integrated picture of the factors that may affect the eventual deployment of NBS actions following the selection process (**Supplementary Material**).

Eco-Engineering Indicators

Indicators conveying information related to eco-engineering functions can be envisaged after the context and problem have been described with context indicators (**Section 4.2**). We assumed that the NBS action will contribute to manage and/or to regulate those drivers and variables triggering and influencing landslides and erosion. Consequently, the eco-engineering performance of the NBS action can be quantified through the assessment of these drivers and variables during the monitoring stage (**Figure 3; Table 1**; also see **Supplementary Material** for full description of eco-engineering indicators). For the case of NBS actions against landslides and erosion, eco-engineering indicators should inform on how the NBS actions contribute to regulate the hydro-climatic and land surface indicators (**Figure 3**), constituting the set of bio-geophysical indicators contributing to eco-engineering performance (**Table 1**), thus being classified herein as KPIs. The indicators portraying the engineering performance of the NBS, which are also classed as KPIs, can be established on the basis of the internal stability and resilience/durability of the NBS action or structure, supplemented with hazard-specific indicators, which they can be assessed using geotechnical engineering principles (Jones, 1996).

The identification and subsequent selection of metrics for the pool of identified eco-engineering KPIs was undertaken on the basis of reviewing textbooks and manuals for standard civil/geotechnical engineering practice (e.g. Eurocode Standards EN-1997-1; Jones, 1996), from which one can gain insight into the principles of slope stability and protection to manage landslides and erosion problems, and into the mechanisms and mathematical principles by which retention walls (e.g., cribwall; **Figure 1C**) and slope 'skins' (e.g., slope grating; **Figure 1D**) contribute to the management of the hazards under concern (e.g., Gray and Sotir, 1996). Once the key metrics were identified, we proceeded with the quick scoping process of the peer-review literature, to identify metrics by which the living component of the NBS (i.e., vegetation) can contribute to regulate these metrics (e.g., Norris et al., 2008). The collection of metrics for each eco-engineering KPI is gathered in **Table 1**. The scoping process also helped to set/propose thresholds for each quantitative metric (**Table 1 and Supplementary Material**), which were established herein on the basis of metrics' values worsening the occurrence of landslides and erosion, or affecting

negatively to the NBS performance. However, we think that the creation of compound, performance indicators supplemented with sensitivity analyses (i.e., break-point analysis) can help to elucidate indicator thresholds (e.g., Toms and Lesperance, 2003; Section 5).

Socio-Ecological Indicators

Insights into the socio-ecological performance of NBS actions against landslides and erosion are of the utmost importance to evaluate the overall performance of NBS and, more importantly, to promote their public acceptance, upscaling, and reproduction (Saleh and Weinstein, 2016; Raymond et al., 2017; Laforteza et al., 2018). Consequently, socio-ecological indicators were classified as KPIs. The socio-ecological performance has to be measured using multiple qualitative methods of assessment such as focus groups, surveys, and observations. The establishment of baselines and thresholds for socio-ecological KPIs is often more challenging than for eco-engineering KPIs, as they are more intrinsically linked to not only the demographic and socio-economic characteristics of the community under question, but are influenced by the needs, expectations and priorities that emerge through the stakeholder mapping and engagement processes (see Sections 2, 3.1 and 3.2; Durham et al., 2014; Table 1). These subjective matters are further compounded when considering the upscaling of NBS (Section 4.6); a large scale NBS project may contain multiple communities with differing socio-economic profiles, and stakeholder priorities, and therefore require a carefully considered approach to measuring KPIs at both the micro and macro scales.

Socio-ecological KPIs are partially informed by socio-economic and ecological metrics, and partly through the stakeholder mapping and engagement process (Section 3.1; Table 1; also see Supplementary Material for full description of socio-economic indicators). They relate to the ecosystem services and co-benefits associated with the NBS actions, with the costs and benefits related to the intervention and with the site-specific risks encountered in the emerging context (Figures 2, 3; Table 1). Socio-ecological KPIs can thus include those directly resulting from the NBS, such as the public accessibility to natural spaces and the perceived aesthetic quality of the community (Sutton-Grier et al., 2015; Keesstra et al., 2018; Table 1), or the regulation of the water cycle at the landscape level or the promotion of plant diversity and soil fauna (Keesstra et al., 2018; Table 1), as well as those indirectly related to the NBS, such as benefits to physical and mental health, the increase in employment opportunities, the increase in property value, or avoidance of damage costs (van den Bosch and Sang, 2017; Wild et al., 2017; Table 1). There are also socio-ecological KPIs relating to community cohesiveness through an increase in stakeholders involved in hazard mitigation projects, which could be classified as the provision of cultural value and heritage by the NBS (Keesstra et al., 2018; Table 1). To assess the economic performance of a NBS action against landslides and erosion, we identified financial KPIs feeding into cost-benefit analyses (e.g., Vicarelli et al., 2016), comparing, for example, whether the life cycle costs of a NBS action would be lower than those of a traditional 'grey' solution because of the absence of structural

concrete and steel, the use of natural materials, lower maintenance costs and the carbon footprint offset of the construction provided by the used vegetation.

Upscaling Indicators

To scale up NBS actions against landslides and erosion, it is essential to provide evidence during the monitoring stage to build confidence in NBS and promote their uptake by the public and private sectors, encouraging decision and policy makers to include NBS in their agendas (Sarabi et al., 2020). To do so, we believe that four main fronts or dimensions across the socio-ecological and eco-engineering compartments need assessment during the monitoring stage of the NBS actions (Figures 2, 3; also see Supplementary Material for full description of upscaling metrics), from which upscaling metrics can be retrieved (i and ii) ecosystem services and risk perception: it is essential to demonstrate with supporting stories and examples how NBS actions are able to provide multiple benefits and co-benefits to human communities whilst contributing to reduce risks and changing the perception towards them by exposed and vulnerable communities (iii and iv) hazard mitigation and bio-geophysical environment: it is also essential to prove that specific NBS actions are in fact able to provide the functions for which they were designed and thus contribute to manage and mitigate landslides and erosion through the positive transformation of the bio-geophysical environment in which they were deployed. The latter would provide valuable evidence on the ability of NBS actions to promote climate adaptation, which is a key issue to reach global movements for NBS (IEEP, 2020). It has been established that local communities are more accepting of NBS—and more willing to participate in their deployment—when they have tangible evidence of the ability of it to prevent or significantly reduce impacts from HHMs (Anderson et al., 2021). Ergo, the evidence of effective mitigation of landslides and erosion through NBS could not only provide a scientific evidentiary basis to support the upscaling of NBS, but also create NBS advocates within communities to drive this upscaling.

DISCUSSION AND CONCLUSION

We proposed a systems-based framework that captures heuristically and holistically the complexity of the context in which NBS actions against landslides and erosion are established. The latter strives to facilitate the monitoring process of NBS performance over time with multi-functional KPIs (Figures 2, 3; Table 1 and Supplementary Material) together with context, selection and upscaling metrics and indicators (Supplementary Material), which were identified through a process of system analysis stimulated by the framework. We thus believe that the proposed framework can have a positive impact on the operationalisation of NBS actions against landslides and erosion, and on the establishment of an evidence base supporting future upscaling activities.

The 'rocket framework' (Figure 2) can help to provide a simplified, yet integrated, portrait of the landscape in which NBS against landslides and erosion are deployed, and to

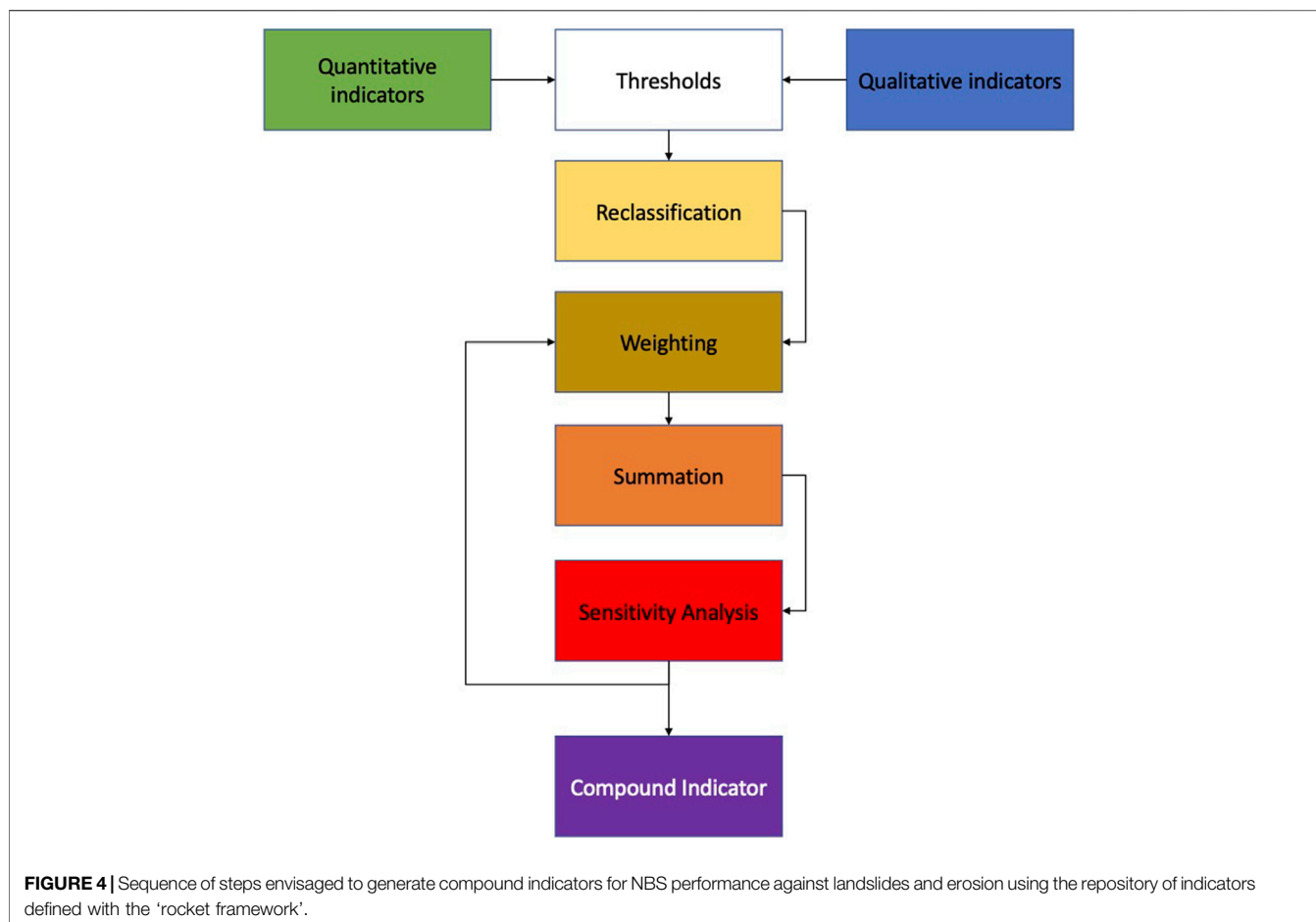
facilitate monitoring of the multi-functional performance of NBS by incorporating the relationships and feedbacks between social, economic, environmental, and engineering components, connecting the socio-ecological and bio-geophysical components of risk (**Figure 3; Table 1**; Gardner and Dekens, 2007). The 'rocket framework' is dynamic, as it interconnects the project stages to assess hazards and risks under changing, emerging contexts resulting from the functions and services provided by NBS actions over time (**Figures 2, 3; Table 1**). The latter supports the implementation of adaptive management strategies in the event of unsatisfactory NBS performance against landslides and erosion (Cohen-Sacham et al., 2019). The 'rocket framework' is flexible, as it is generic enough to incorporate different pools of indicators than the proposed herein (**Table 1** and **Supplementary Material**) to meet the needs of different contexts and challenges (i.e., different HMHs than landslides and erosion), and it is also versatile, as it can be used at different project stages to identify problems, compare alternatives, or monitor performance of established NBS.

A novel key aspect of the 'rocket framework' is that it integrates, for the first time, components related to eco-engineering performance in a NBS framework tailored to landslides and erosion (**Figure 2; Table 1**). We think that this is essential when NBS actions focus on infrastructure necessitating the intrusive intervention of the ecosystem/landscape to address the challenge under concern, as is the case for landslides and erosion. NBS are planned to solve a specific problem (or a series of them), so it is essential to be able to quantify how well a given NBS is doing with solving the problem under concern. The eco-engineering domain clearly established the scope and objective of the selected NBS actions detailed in the case study - e.g., slope stability and ground protection with live cribwall and vegetated slope grating (**Figures 1C,D**). It also provided a platform with a series of tangible, standard measures to quantify the effect of the NBS actions against the identified problems (**Table 1**). Additionally, the eco-engineering domain helped articulate the thinking process overarching other domains and dimensions depicted in the 'rocket framework', thus facilitating the identification process of KPIs (**Table 1**). The engineering performance of green infrastructure interventions is often taken for granted, as it is based on rigorous design and planning. As a result, this domain is often excluded from the pool of functions and benefits that NBS can provide. However, the eco-engineering domain may help envision how technology and nature blend together to provide solutions for specific challenges and to provide benefits to the society. Building upon the case study explored herein (**Section 2**), we provide an example to cast some light on how the eco-engineering domain of the 'rocket framework' helped to articulate the identification and selection of KPIs for the selected NBS actions against landslides and erosion (**Table 1** and **Supplementary Material**).

The chances of landslides and erosion events will be substantially reduced under flat topographies (e.g., Panagos et al., 2015), under well-structured, well-reinforced and relatively dry soil (Lu and Godt, 2013), and under an

ecosystem/landscape that is resilient to change and disturbance brought by the hazards (Walker, 2013; Gonzalez-Ollauri and Mickovski, 2017c). Thus, the selected NBS actions against landslides and erosion should potentially modify the site topography by reworking and flattening the slope where they are deployed (i.e., re-grading; Norris et al., 2008). The timber structure of the NBS actions (**Figures 1C,D**) and their living components (i.e., plants) should reinforce mechanically the ground either through the insertion of new structural elements in the soil such as timber members, steel/wooden nails or plant roots (e.g., Jones, 1996; Gonzalez-Ollauri and Mickovski, 2017d), or through, for example, the long-term incorporation of organic matter to the soil originating in the decay of plant parts (e.g., Adamczyk et al., 2019). The establishment of a dense vegetation cover on the NBS structure (**Figure 1C**) should promote drainage and water uptake, overall leading to drier soil conditions (Gonzalez-Ollauri and Mickovski, 2017b; Gonzalez-Ollauri and Mickovski, 2020a) and to the regulation of the local climate (Osborne et al., 2004). Moreover, the establishment of the vegetation cover on the NBS will contribute to intercept rainfall (Gonzalez-Ollauri and Mickovski, 2017b), to reduce the mechanical impact of raindrops on the soil (Vaezi et al., 2017), to regulate the temperature in the soil (Gonzalez-Ollauri et al., 2020b), to stimulate the colonisation by soil fauna and native flora, and much more (e.g., hosting pollinators and birds; seed dispersal, pest regulation, resistance to windstorms, etc. Brockerhoff et al., 2017); providing overall resilience towards change and disturbance and making the ecosystem more complex and stable (Pimm, 1984). Plant establishment and development will make the intervened landscape aesthetically pleasant (Smardon, 1988), encouraging recreational activities within the intervened area, such as walks or birdwatching (Shanahan et al., 2015), and fostering the positive perception and acceptance of the NBS actions by the human communities exposed to landslides and erosion such as the community at OAL-UK (**Section 2**); provided that effective communication and engagement with the end-users is established to increase their awareness of the benefits (Anderson and Renaud, 2021). The stabilisation of the slope with a solid, timber structure that eventually merges with the local landscape (**Figures 1C,D**) will also have a positive impact on the risk awareness and perception by the affected community.

The example provided above illustrates the connection between the eco-engineering and socio-ecological domains established in the 'rocket framework' (**Figures 2, 3**) in a context of landslides and erosion management and mitigation. It also draws an example about the thinking process by which additional domains, compartments, and indicators unfolded through the critical analysis of the system, problems, and solutions, using the eco-engineering domain as driver. The latter stresses the value of including the eco-engineering domain in the monitoring process of NBS performance against landslides and erosion, as it allows envisioning how technology and nature blend together to provide solutions for specific challenges. Thus, we believe that the 'rocket framework' and its associated analytical approach, by which it was conceived and



supplemented, can provide a good basis for the operationalisation of NBS actions against landslides and erosion, and for the quantification of their multi-functional performance through monitoring activities. It is worth noting that although the 'rocket framework' was conceived in a context of landslides and erosion, its dimensions and components were defined from a generic standpoint to enable reproducibility in other contexts and with different HMHs. However, it was beyond the scope of this study to provide the reader with a method to compute the overall performance of the NBS actions with the 'rocket framework' (Figure 2) and the KPIs and metrics identified (Table 1). The combination of numerical modelling, multi-criteria (MCA) and cost-benefit analyses is generally proposed in the literature to undertake such a task (e.g., Raymond et al., 2017). However, only few studies have attempted to combine multiple KPIs in the context of NBS performance to then provide a system of NBS scores or grades (e.g., Watkin et al., 2019). Hence, future studies should strive to address this gap by proposing and validating robust, numerical approaches that combine multiple quantitative and qualitative variables from the KPIs repository with the aim of producing a compound index or score conveying reliable information on NBS performance against landslides and erosion. We envisage that such approaches should at least involve the following four steps stemming from MCA (Figure 4):

- 1) reclassification: to change the values of one variable into other values, putting different variables on the same scale. With this step, a new score scale can be established for reclassifying the values of a given variable/indicator into intervals or groups. This process becomes easier when thresholds for a given indicator are identified (Table 1 and Supplementary Material). Reclassification can also be useful to transform qualitative into numerical variables.
- 2) weighting: to allocate a measure of importance to the different variables or indicators involved in calculating NBS performance against landslides and erosion. It could be assumed that all the indicators are equally important but, most likely, some indicators are more relevant than others upon determining NBS performance. The weighting process can be supplemented with correlation and sensitivity analyses and/or with regression modelling when enough data are available, so only uncorrelated indicators are considered to compute the NBS performance score, and so trade-offs and synergies between indicators can be detected (Gonzalez-Ollauri and Mickovski, 2017e). Expert-driven techniques, such as the analytical hierarchy process (Saaty, 1980), can help identify objectively the relative importance of the different indicators involved (Gonzalez-Ollauri et al.,

2020b), but it is still important that only uncorrelated, independent indicators are taken to the next step.

- 3) summation: to combine the multiple indicators together and calculate the NBS performance score; once the indicators have been standardised, reclassified, and different weights allocated to each of them. The most widely approach to do so is the simple additive weighting (SAW; Hwang and Yoon, 1981). Yet, machine learning algorithms such 'boosted regression trees' (Breiman et al., 1984) and 'random forest' (Breiman, 2001) may open-up an exciting opportunity to combine multiple indicators, whether raw or processed, whether qualitative or quantitative, to retrieve scores or indices of NBS performance against landslides and erosion.
- 4) sensitivity analysis: to assess how the uncertainty in the NBS performance score can be allocated to the different indicators used and dismiss those indicators that do not significantly contribute to the output. If the uncertainty of the performance score is high, uncertainty filtering techniques can be implemented (e.g., Malkawi et al., 2000). Also, this step can help identify indicator thresholds through break-point analysis (e.g., Toms and Lesperance, 2003).

There is a pressing need to work along with nature to sustainably address current and future societal challenges that stem from environmental and climate change (e.g., EU Strategy on Green Infrastructure). Nature-based solutions against landslides and erosion open-up an exciting opportunity to do so, but they need upscaling, so their effect can be noticeable (Cohen-Sacham et al., 2019). There is, however, a severe lack of evidence on NBS performance (e.g., Nelson et al., 2020; Ruangpan et al., 2020) which hinders the operational rigour of NBS, it undermines the trust society has in them, and it slows down the upscaling and overall uptake of NBS. Filling the knowledge gap on NBS performance against landslides and erosion is an ambitious challenge that will require the close cooperation between scientists, practitioners, end-users, human communities, and decision and policy makers. In this study, we are providing a novel holistic framework based on the experience from a relevant case study that strives to facilitate addressing the lack of NBS performance evidence against landslides and erosion by helping to articulate the thinking process involved with mapping out effective monitoring strategies throughout the project timeline, thus helping identify problems, solutions, and performance indicators holistically. Herein, we are also refocusing the spotlight towards green infrastructure and eco-engineering techniques, which hold valuable experimental practice and knowledge to help build upon the evidence base on NBS against landslides and erosion, and their subsequent standardisation. This research showcases the benefits of engaged research which represents collaboration between a multidisciplinary academic research team which is seen as essential to help to shape the holistic coverage of the indicators,

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and also the co-creation process with community stakeholders at OAL-UK, which was deemed essential for ensuring local context is reflected and in gaining buy in through a shared mutual benefit between academics and the community on a theoretical and practice-based level. An iterative approach which promotes inclusion of actors and enables reflexivity throughout is deemed key to helping promote the conditions for co-creation. Future work will showcase the implementation of the proposed framework and KPIs repository in the OAL-UK, from which a reproducible approach to score NBS performance against landslides and erosion will be devised.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

AG-O: Conceptualisation, Data curation, Investigation, Methodology, Project administration, Visualization, Writing—original draft, Writing—review and editing. KM: Investigation, Methodology, Writing—original draft. CT: Methodology, Writing—original draft. SM: Supervision, Writing—original draft, Writing—review and editing. RE: Funding acquisition, Supervision, Writing—review and editing.

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SUPPLEMENTARY MATERIAL

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