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Slope Processes, Mass Movement and Soil Erosion: A Review

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ABSTRACT

Soil erosion and land degradation are global problems and pose major issues in many countries. Both soil erosion and mass movement are two forms of land degradation and humans play important roles in these geomorphological processes. This paper reviews slope processes associated with mass movement and soil erosion and contributory factors, including physical and human agents. Acting together, these cause diverse geomorphological features. Slope processes are illustrated by reference to case studies from Brazil and UK. The causes and impacts of erosion are discussed, along with appropriate remedial bioengineering methods and the potential of the measures to prevent these types of environmental degradation. Although there are several agents of erosion, water is the most important one. Cultivation can promote soil erosion, due to ploughing and harvesting, which moves soil down slopes. Soil erosion and mass movement data would inform the viability of soil conservation practices. Integrated management of drainage basins offers a promising way forward for effective soil conservation and soil remedial bioengineering in Brazil and UK.

Key Words: geomorphological feature, land degradation, hazards, risks, slope processes, soil recuperation

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INTRODUCTION

The dominant hillslope processes are associated with gravity and running water. Human activities play important roles in hillslope processes, due to land use changes and vegetation clearance, both in rural and urban areas. These processes can be accentuated by climate changes (Varnes, 1978; Trudgill, 1988; Selby, 1993; Goudie, 1995; Cendrero and Dramis, 1996; Cruden and Varnes, 1996; Goudie and Viles, 1997; Favis-Mortlock and Guerra, 1999; Fullen, 2003; Fullen and Catt, 2004; Crozier and Glade, 2005; Van Westen *et al.*, 2008; Kanungo and Sharma, 2014; Shafiq *et al.*, 2014; Arbuckle *et al.*, 2015; Agnihotri and Kumar, 2015). The causes and consequences of both sets of processes and the importance of monitoring these processes have been studied, in order to understand how they occur and can be prevented (Thomas and Allison, 1993; Ellis and Mellor, 1995; Lascelles *et al.*, 2000; Valentin *et al.*, 2005; Bochet *et al.*, 2006; Kitutu *et al.*, 2009; Nadal-Romero *et al.*, 2014; Vanmaercke *et al.*, 2016). In addition, once they do occur, we consider potential recuperation technologies (Fullen *et al.*, 1995; Subedi *et al.*, 2009; Bhattacharyya *et al.*, 2010, 2011; De Baets *et al.*, 2011; Fullen *et al.*, 2011; Subedi *et al.*, 2012; Dhital *et al.*, 2013; Fullen and Catt, 2014; Guerra *et al.*, 2015).

Proactive management of vegetation systems are essential for effective recuperation (Trudgill, 1988; Tiffen *et al.*, 1994; De Baets *et al.*, 2011; Fullen *et al.*, 2011; Bhattacharyya *et al.*, 2012; Dhital *et al.*, 2013; Fullen and Catt, 2004; Guerra *et al.*, 2015). Accelerated erosion is one of the greatest problems of land degradation because it seriously depletes fertile topsoil. The removal of original vegetation for agricultural purposes is one of the main factors causing soil erosion. The general forms of soil erosion by water include sheet, rill and gully erosion.

Geomorphic activity is usually a critical determinant of damage. Each of the two geomorphic processes has specific causal factors, such as vegetation clearance, rainfall intensity, rainfall volume, slope angle, soil properties, land use and land management, which affect soil erosion and mass movement, both in urban

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and rural areas. Depending on the frequency and magnitude of each one of these factors, catastrophic landslides might occur.

The role of mass movement and associated geomorphological processes have been studied, along with the diagnostic parameters to recognize different types of mass movement in the field (Varnes, 1978; Brunsden, 1988; Goudie and Viles, 1997; Crozier and Glade, 2005; Morgan, 2005; Lin *et al.*, 2006; Van Westen *et al.*, 2008; Van Den Eeckhaut *et al.*, 2010; Clague and Robert, 2012; Guzzetti *et al.*, 2012; Kanungo and Sharma, 2014), especially in Brazilian and British (Selby, 1993; Goudie and Viles, 1997; Fullen and Catt, 2004; Coelho Netto *et al.*, 2007; Guerra *et al.*, 2007; Graeff *et al.*, 2012; Petrucci *et al.*, 2013; Guerra and Jorge, 2014).

Selby (1993) outlined that mass movement (or mass wasting) is the movement of soil and/or rock downslope, under the influence of gravity, being a collective material movement, without necessarily being influenced by water or ice. Nevertheless, water or ice may decrease the shear strength of slopes, and thus soils physically behave as plastics or, in very moist conditions, as fluids (Abrahams, 1986; Brunsden, 1988; Selby, 1993; Goudie and Viles, 1997; Clague and Robert, 2012; Kanungo and Sharma, 2014; Guerra and Jorge, 2014). This might, consequently, make mass movement even more catastrophic, causing destruction and even mortalities.

Soil erosion and land degradation are global problems and pose major issues in many countries, including Brazil. The hazards affect both urban and rural areas within the extensive national territory (8 547 403 km^2). In turn, these problems have serious environmental and socio-economic impacts (Guerra *et al.*, 2014). It is important that soils be conserved, for present and future generations. Although erosion is a natural phenomenon, often human activities accelerate erosion processes. Erosion may occur naturally, due to slope angle and rainfall. Some surveys exemplify this, often based on stratigraphical and archaeological evidence within valley floor deposits. For instance, natural soil erosion has been reconstructed in North Germany from the early Holocene, when soil developed under natural woodlands, up to the early Middle Ages, when erosion rates were still very low (Bork, 1989). Furthermore, Dotterweich (2009) and Dreibrodt *et al.* (2010) have discussed soil erosion during the Holocene. During the Neolithic (about 7 500 years BP), many areas of central European soil have been washed downslope by soil erosion and gullies have incised, leading to the development of colluvial and alluvial deposits (Dotterweich, 2009). Soil erosion on US agricultural soils causes the loss of an average of 30 t ha^{-1} year^{-1}, some eight times greater than rates of soil formation. A survey by Brazilian Agricultural Research Corporation (EMBRAPA) suggested the situation in Brazil is often worse, reaching 60 t ha^{-1} year^{-1} in southeastern Brazil (Manzatto *et al.*, 2002). According to Goudie and Boardman (2010), it is quite clear that the major areas of intense erosion are associated with both human and natural factors. Boardman (2006) suggested the following countries/regions are global erosion hotspots: the Loess Plateau of China, Ethiopia, Swaziland, Lesotho, the Andes, South and East Asia, the Mediterranean basin, Iceland, Madagascar, the Himalayas, the Sahel of West Africa, the Caribbean and Central America. We propose Brazil is also an erosion hotspot (da Silva *et al.*, 2005; Gurgel *et al.*, 2013; Guerra *et al.*, 2014; Nacinovic *et al.*, 2014).

Although both soil erosion and mass movement are two forms of land degradation and humans play important roles in these geomorphological processes, they present different modes of occurrence and consequently different ways of being identified and monitored and they also present diverse features (Varnes, 1978; Small and Clark, 1982; Abrahams, 1986; Hart, 1986; Brunsden, 1988; Gerrard, 1992; Evans, 1993; Selby, 1993; Guerra, 1994; Goudie and Viles, 1997; Favis-Mortlock and Guerra, 1999; Fullen and Catt, 2004; Crozier and Glade, 2005; Morgan, 2005; Lin *et al.*, 2006; Shukla *et al.*, 2006; Van Beek *et al.*, 2008; Van Westen *et al.*, 2008; Goudie and Boardman, 2010; de Vente *et al.*, 2011; Boardman and Favis-Mortlock, 2014; Kanungo and Sharma, 2014; Orimoogunje, 2014; Sun *et al.*, 2014; Guerra *et al.*, 2015; Monsieurs *et al.*, 2015; Vanmaercke *et al.*, 2016). Nevertheless, the best way to avoid both forms of land degradation is acting preventively, which means to understand the risks of soil erosion and/or mass movement, in order to avoid them. In this respect, Orimoogunje (2014) stated that conservationism emphasizes the need to guarantee a sustainable supply of productive land resource for future generations. Preservationists seek to protect scenery and ecosystems in a state as little affected by humans as possible.

Climate regimes play an important role in both soil erosion and mass movement processes. With regard to rainfall, over a long period, most erosion occurs during events of moderate frequency and magnitude, because catastrophic events are not so frequent so as to cause a great amount of net erosion. This is a short-term perspective: when high magnitude events occur, soil loss is much higher than during moderate rainfalls;

heavy precipitation events are the main reason for the incision of gullies in many landscapes (Dreibrodt and Wiethold, 2015). The same applies to mass movement, taking into account the main factors that affect this geomorphological process (*i.e.*, slope angle and shape, soil properties, vegetation cover, soil depth, the interface between soil and the underlying rock, vegetation clearance, human factors, such as slope talus cuts, lack of soil drainage and sewage and unpaved roads). At a long temporal scale, the relationship between landslide activity and triggering mechanisms can be established from the temporal clustering of dated landslides (Borgatti and Soldati, 2010). In this review, over 100 publications are surveyed, and the studied aspects included soil erosion, soil erodibility, soil erosivity, soil properties, soil types, slope angle, length and shape, vegetation cover, vegetation clearance, climate change and land use and management. The comprehensive literature survey is based on articles mainly in 2000–2015, but also some pre-2000 literature. The main geo-environmental features of a region and their different effects on the occurrence of landslides and soil erosion are described in detail. To achieve this, several factors have been addressed, and are illustrated using examples from Brazil and UK. Soil erosion and mass movement have attracted thousands of studies across the world. Although both processes constitute forms of land degradation, we describe them separately in this review.

MASS MOVEMENT

Selby (1993) concisely described mass movement, or mass wasting of soils, as the movement of soil and/or rock, downslope, under gravity, of collective materials, without necessarily water or ice action. Varnes (1978) developed a mass movement classification based on the material (mud, soil, earth, rock and debris) and movement type (falls, topples, slides (rotational and translational), lateral spreads and flows). Varnes (1978) also proposed a further movement type, which he named complex; this type is a combination of two or more principal types of movements. These movements are outlined and some examples are presented below. When there is the action of water and/or ice, the agents may decrease soil shear strength and, consequently, contribute to the plastic or liquid behaviour of soil, making mass movement even more catastrophic (Varnes, 1978; Hansen, 1984; Brunsden, 1988; Goudie, 1995; Cendrero and Dramis, 1996; Goudie and Viles, 1997; Crozier and Glade, 2005; Van Beek *et al.*, 2008; Van Westen *et al.*, 2008; Fell *et al.*, 2012; Graeff *et al.*, 2012; Korup, 2012; Petrucci *et al.*, 2013; Guerra and Jorge, 2014; Kanungo and Sharma, 2014). Surveys of mass movement have different aims, including predicting their occurrence, which depends on several factors. Therefore, care is required with the interpretation of site characteristics. Undoubtedly, any judgement on mass movement hazards will be subjective and it is strongly advised that local expertise is consulted, as distinct conditions may be important for the initiation and reactivation of mass movement in a given region (Van Beek *et al.*, 2008). Therefore, the geomorphological investigation of mass movement may provide a framework to describe and map surface landslide processes and to predict future process behaviour (Brunsden, 1988; Selby, 1993; Griffiths and Whitworth, 2012; Kanungo and Sharma, 2014). Guzzetti *et al.* (2012) recommended that to prepare a landslide map, a legend is required and the legend must meet the project goals, must be capable of portraying relevant geomorphological characteristics and must be compatible with the technique used to capture the information.

Several studies have monitored mass movement dynamics (Goudie, 1995). Petley (1984) described the main objectives of surveys of mass movement as: 1) to understand the development of natural slopes and the processes that contribute to the formation of new features; 2) to make it possible to stabilize slopes under different conditions; 3) to determine risks of landslide or other forms of mass movement on both natural and artificial slopes; 4) to facilitate recuperation on slopes which have experienced mass movement and to plan land use types which include preventive measures so that those geomorphological processes do not recur; 5) to analyse the various types of mass movement and assess the causes and consequences of these processes and 6) to know how to respond to external factors influencing slope stability, such as earthquakes, which also play important roles in triggering mass movement.

Many studies have addressed the important issues of mass movement hazards and risks. Crozier and Glade (2005) highlighted that the level of risk is the combination of the likelihood of adverse occurrences and the consequences if it does. The level of risk results from the intersection of hazard with the value of the elements at risk by way of their vulnerability.

There are different types of mass movement. Therefore, the different definitions used and the physical principles which underlie mass movement must be explained and the diagnostic parameters to explain how to recognize different types of mass movement in the field are fundamental. The main types of mass movement are falls, slides and flows (Varnes, 1978; Brunsden, 1988; Selby, 1993; Van Beek *et al.*, 2008; Clague and Robert, 2012). There are many causes for mass movement, including deforestation, adverse hydrological conditions, slope undercutting, climate (precipitation/thawing of ice), geology (water impermeable layers and swelling clays), earthquakes and volcanic eruptions. In addition, meteorological events, such as heavy rainstorms, inducing water infiltration and increased pore water pressure, and increased air temperatures, inducing the melting of glacial or ground ice (Cendrero and Dramis, 1996), are also the causes of mass movement.

The most common and catastrophic mass movement is landslide. According to Clague and Robert (2012), each year, landslides are responsible for hundreds of millions of dollars' worth of damage and, on average, claim more than 1 000 lives around the world. Although most common in mountainous areas, landslides can occur anywhere with enough local relief to generate gravitational stresses capable of causing rock or soil to fail (Figs. 1 and 2). They may be one of the most damaging and deadly of the natural hazards in the world, and the data available from the Centre for Research on the Epidemiology of Disasters (CRED), located in Leuven, Belgium, suggest that landslides were responsible for over 10 000 deaths and left 2.5 million people homeless between 2001 and 2010 (CRED, 2011). Another useful definition of landslides is proposed by Korup (2012), who stated that landslides are the downhill and outward movement of slope-forming materials under the influence of gravity and also, in most cases, water. Mostly triggered by earthquakes, rainstorms, snowmelt and slope undercutting, they are among the prime producers of sediment and major agents of denudation. In fact, although there are different types of mass movement, it is very common amongst many authors to view landslide as synonymous with mass movement.

Fig. 1 A landslide scar formed due to heavy rainstorms in April 2013 in Petrópolis Municipality, Rio de Janeiro State, Brazil. The house was condemned on safety grounds (photo by Antonio Jose Teixeira Guerra).

Fig. 2 House destroyed by a landslide in April 2013 in Petrópolis Municipality, Rio de Janeiro State, Brazil. This caused the death of 3 people (photo by Antonio Jose Teixeira Guerra).

Mass movement has been surveyed by many disciplines, including geologists, geomorphologists and engineers. They have used different approaches, but all of them are concerned with understanding the processes, in order to be able to propose ways to assess and, consequently, to avoid them (Morgan, 2005). The amount of sediments transported by mass movement to rivers is much greater than that transported by rills and gullies (Morgan, 2005). It is extremely important to predict mass movement. An initial step is to construct accurate and reliable maps that can be used to assist the prediction of landslide hazards and risks in a specific area. It is crucial to seek insights into the spatial and temporal frequency of landslide, and therefore each landslide hazard or risk study should start by making a landslide inventory that is as complete as possible, both in space and time (Van Westen *et al.*, 2008). Consequently, by mapping and dating the phenomena present in the landscape, we become able to: 1) outline hazardous zones (mapping and comparison with geological and relief data) and 2) consider recurrence intervals and relevant processes (such as dating and comparison with palaeoclimatic data, palaeovegetation data and historical land use data).

In a survey in Ubatuba Municipality (São Paulo State, Brazil), deforested steep slopes were the necessary preconditions for mass movement, which was then triggered by heavy rainstorms (Guerra and Oliveira, 2009). In Ubatuba, these natural conditions can be accentuated by unplanned settlements. Urban expansion was accelerated after the construction of the

Rio-Santos Highway, attracting many tourists to this area and, consequently, promoting rapid construction of houses and resort buildings, without respecting environmental risks (Fig. 3). House construction has tended to move beyond the densely settled coastal plains onto adjacent hillslopes, which are often steep. This poses problems to both residents and tourists (Souza and Suguio, 2003; Ferreira *et al.*, 2005; Guerra and Oliveira, 2009; Mendes and Filho, 2015). Ubatuba is infamous for landslides. In general, the major natural constrains that are responsible for translational landslides in this area include high slope steepness (usually over 30°), which is associated with morphology (concave and/or linear geometry), and the presence of seasonal apparent cohesion, which results from saturated soil profiles and high rainfall (cumulative and/or hourly rainfall intensity) (Mendes and Filho, 2015).

Fig. 3 Shallow landslide scar on Rio-Santos Highway, Ubatuba Municipality, São Paulo State, Brazil, in December 2009 (photo by Maria do Carmo Oliveira Jorge).

Guerra *et al.* (2007) conducted a comparable survey and analysed mass movement in Petrópolis Municipality, Brazil, where 50 people died in 2001 due to landslides caused by about 200 mm of rain in 24 h. In 2011, another heavy rainfall of 240 mm in 24 h caused landslides that resulted in the deaths of 71 people in the same Municipality (Graeff *et al.*, 2012). Very similar conclusions were arrived at in both surveys. The main causes of these catastrophic geomorphological processes were both natural (*i.e.*, heavy rainstorms and steep slopes) and human factors (*i.e.*, unplanned settlement, vegetation clearance, unpaved roads and lack of appropriate sewage systems and rain-water conduits). These findings agree with Trudgill (1988), who outlined that mass movement can be seen from the perspective of their relationships between natural components and responses to slope perturbations. Trudgill (1988) identified that mass movement usually starts with vegetation clearance, although in some cases it might occur on vegetated slopes. Furthermore, soil and vegetation systems are complex, and one of the main associated problems is the application of the stability concept. Some subcomponents of the system will experience more changes than others (Brunsden, 1988; Gerrard, 1992; Hasset and Banwart, 1992; Selby, 1993; Goudie and Viles, 1997; Morgan, 2005; Van Beek *et al.*, 2008; Clague and Robert, 2012; Fell *et al.*, 2012; Korup, 2012; Brunetti *et al.*, 2014).

In Brazil, the Rio de Janeiro-Ubatuba Highway, which connects Rio de Janeiro and São Paulo States, has attracted many people, who often build their houses on steep slopes. This type of urban settlement on these steep slopes has been responsible for many landslides, especially in recent years (Fig. 4). They have caused the death of dozens of people and severe material losses (Ferreira *et al.*, 2005; Guerra and Jorge, 2009; Guerra *et al.*, 2013; Mendes and Filho, 2015).

Often there are time-lags between the deforestation of steep slopes and the onset of mass movement. On forest clearance, tree roots remain largely intact and

Fig. 4 Landslide scar in Angra dos Reis Municipality, São Paulo State, Brazil. Over 40 people died within the municipality due to landslides associated with about 200 mm of rain in 24 h in December 2009 (photo by Antonio Jose Teixeira Guerra).

thus maintain slope stability. Roots can act as environmental nails which retain soil in place. However, tree roots will undergo decomposition processes and these processes are usually rapid in the humid tropics. Thus, after about two years the environmental-nail effect is lost and slopes enter a precarious phase of potential instability (Goudie and Viles, 1997; Brunetti *et al.*, 2014; Nadal-Romero *et al.*, 2014).

The response of slopes to the different ways they are occupied depends on several factors, including the existing soils, slope angle and shape and human intervention. In recent decades in Brazil, and several other countries, there has been an increased frequency and magnitude of mass movement, partly due to physical environmental variables, but mainly due to the way constructions are built without taking into account the risks posed by the natural triggers at each site. Brunsden (1988) pointed out that planners need to know the risks to slopes due to the kind of occupation. This is also emphasized by Small and Clark (1982), who outlined the role of humans when they alter the landscape, and they called this process the production of artificial slopes, which is particularly important on a local scale.

Local governments should obtain detailed information from scientists (geographers, geomorphologists, civil engineers, architects, planners, ecologists, soil scientists and geologists), in order to avoid the occurrence of mass movement, and consequently, loss of lives and property (Brunsden, 1988; Hooke, 1988; Trudgill, 1988; Goudie and Viles, 1997; Guerra *et al.*, 2007; Van Beek *et al.*, 2008; Fell *et al.*, 2012; Graeff *et al.*, 2012; Korup, 2012; Guerra *et al.*, 2013; Guerra and Jorge, 2014). Furthermore, Brunsden (1988) stated that in cases of subsequent mass movement, local authorities should be responsible for authorizing the construction of roads and buildings. That is one of the reasons to produce environmental surveys, including slope assessment, before these areas are occupied, so that mass movement risks may be evaluated. In order to assess slope hazards and risks, it is also important to evaluate the rainfall threshold for landslides to occur. Therefore, Kanungo and Sharma (2014) outlined that a threshold may define the rainfall, soil moisture or hydrological conditions that when reached or exceeded, are likely to trigger landslides. This combination of environmental and human variables has to be taken into account in predicting mass movement, in order to avoid them.

SOIL EROSION

Selby (1993) classified soil erosion as a geomorphological process which occurs on hillslopes, carried out by flowing water and splash processes. Selby (1993) termed this erosion on hillslopes by raindrops and flowing water and outlined the role of water in removing and transporting sediments, which he described as wash, a term adopted by many researchers (Gerrard, 1992; Evans, 1993; Goudie and Viles, 1997; Poesen *et al.*, 2006; Goudie and Boardman, 2010; Guerra *et al.*, 2014).

It is important to outline the difference between the natural soil erosion and the accelerated soil erosion. The first one is what we can also call geological erosion, which is water flowing on the soil surface, possibly transporting sediments and, consequently, reducing soil thickness, but over a long period of time, and usually very slowly. In this case, weathering, which occurs on the rocks underneath the soil, can compensate for the eroded soil. Accelerated soil erosion usually occurs on agricultural fields and bare soils and depends on several factors. Therefore, other concepts may be introduced to differentiate between natural and accelerated soil erosion. The natural soil erosion is with respect to soil loss tolerance, and whether this exceeds a limit, it causes land degradation, as rates of soil formation are usually much less than soil loss.

Sediments transported by running water usually pose another environmental problem, that is, the off-site effects of soil erosion. This is becoming a recurrent problem in UK, and therefore, Boardman and Vandaele (2010) outlined that muddy flooding is caused by runoff carrying soil from bare or relatively bare agricultural fields. Documentation of muddy flooding exists for several other European countries, including Belgium, France, the Netherlands, Poland, Slovakia, Germany, Spain and Italy (Boardman and Vandaele, 2010). This is a good example of off-site effects from agricultural fields damaging property, roads and water bodies (rivers, reservoirs and lakes). Evrard *et al.* (2010) reported that in the European loess belt, water flowing from agricultural fields frequently carry large quantities of soil as suspended sediment. These geomorphological processes cause muddy floods in settlements downstream and are generally triggered on silty and loamy soils, which are prone to surface sealing (Boardman *et al.*, 2006). Nevertheless, the best option is that in order to prevent (ephemeral) gullies from developing in cropland, all possible measures leading to an increase in rain infiltration, to a reduction in Hortonian overland flow discharge and hence also to a reduction of flow shear stress need to be applied (Poesen *et al.*, 2006). Consequently, there will be less risk of both on-site and off-site effects of soil erosion. In the European context, most concern is expressed over the damaging off-site effects of soil erosion on water quality and the costs associated with subsequent water purification for water supply systems (Fullen, 2003).

Soil erosion has different classifications, according to the region where it occurs, soil types, precipitation regime, soil properties, slope characteristics, land use and management. Nevertheless, most researchers agree that this process can cause three main features, depending on causal factors and on its evolution. These are sheet, rill and gully erosion (Abrahams, 1986; Selby, 1993; Goudie, 1995; Fullen and Catt, 2004; Morgan, 2005; Valentin *et al.*, 2005; Boardman, 2006; Van Beek *et al.*, 2008; Goudie and Boardman, 2010; Vanmaercke *et al.*, 2012, 2016; Monsieurs *et al.*, 2015). Although the three erosion features cause land degradation wherever they occur, recent field-based studies indicate that: 1) gully erosion is an important soil degradation process in a range of European environments, causing considerable soil losses and producing large volumes of sediment and 2) (ephemeral) gully development increases the sediment connectivity in the landscape and hence also the sediment delivery to lowlands and permanent water courses where gullies aggravate off-site effects of water erosion (Poesen *et al.*, 2006). This is another good example how off-site effects are usually at least as important as on-site effects in soil erosion surveys. Fullen and Catt (2004) outlined that when rainfall intensity exceeds soil infiltration capacity, runoff begins, thus provoking soil erosion. They also stated that the process initiates as sheet erosion, tending to concentrate in minor incisions, forming rills (Fig. 5), which may evolve into gullies (Figs. 6 and 7), as they widen and incise into the soil. Fullen and Catt (2004) admitted that this theme might be polemic. Therefore, they stated that while rills tend to incise mainly into the A horizon, gullies reach easily the B and even C horizons. Sometimes, they even reach bedrock, depending on the magnitude of erosive processes. These are in agreement with several studies (Thornes, 1990; Gerrard, 1992; Selby, 1993; Favis-Mortlock and Guerra, 1999; Morgan, 2005; Valentin *et al.*, 2005; Boardman and Poesen, 2006; Evans, 2006; Goudie and Boardman, 2010; Guerra *et al.*, 2014; Guerra *et al.*, 2015; Labrière *et al.*, 2015; Vanmaercke *et al.*, 2016).

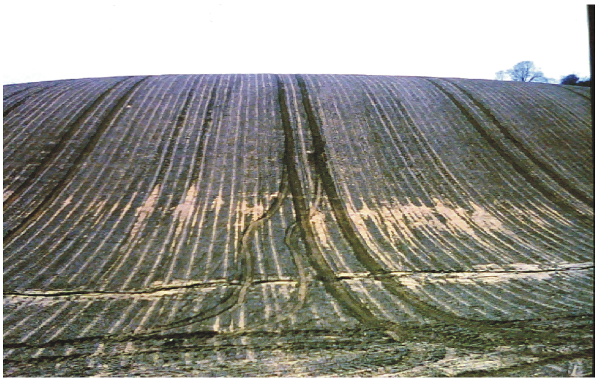

Fig. 5 Rill erosion along cultivation lines in east Shropshire, England, UK (photo by Michael Augustine Fullen).

Fig. 6 Rill and gully erosion due to low-intensity (1.8 mm h^{-1}) rainfall on snowmelt saturated soils at Hilton, east Shropshire, England, UK. Note the shoulder at about 20 cm depth, due to subsoil compaction (Fullen, 1985) (photo by Michael Augustine Fullen).

Fig. 7 Gullies within Bacanga State Park, São Luis Municipality, Maranhão State, Brazil, in January 2015 (photo by José Fernando Rodrigues Bezerra).

Surface runoff is produced due to several factors, including vegetation clearance, agriculture without conservation practices and rainfall regime. When rainfall intensity exceeds infiltration capacity, the excess rain forms surface runoff. This process causes sheet erosion, which might evolve into rill and gully erosion (Gerrard, 1992; Selby, 1993; Morgan, 2005; Goudie and Boardman, 2010; Fullen and Catt, 2004; Guerra *et al.*, 2014; Labrière *et al.*, 2015). As erosion processes at field level are dominated by concentrated rills, these linear erosion features can widen and deepen and cut into the subsoil, thus creating gullies. In addition, depending on the size of the agricultural fields, erosion may produce less soil loss, but the larger the fields, the larger the runoff collection in a catchment. As a result one has to consider different scales, both for surveying and for estimating damages. Enters (1998) reviewed this issue in detail, scaling-up from fields to national levels. From this perspective, Enters (1998) outlined the on-site effects of soil erosion at several hierarchical scales: occurrences at one scale usually influence outcomes at other scales. Furthermore, Izac and Swift (1994) defined five hierarchical levels for measuring soil erosion: cropping system, farming system, catchment system, regional system and supra-regional system.

Soil erosion is a natural phenomenon; *i.e.*, it varies naturally with climate, soils and topography. Therefore, all landscapes which have slopes $> 3°$ may experience some form of erosion (Gerrard, 1992; Selby, 1993; Ashman and Puri, 2002; Fullen and Catt, 2004; Morgan 2005; Evans, 2006; Gumiere *et al.*, 2009; Liu *et al.*, 2014; Sensoy and Kara, 2014). Nevertheless, in Europe, during the Holocene, there was relatively little natural erosion once vegetation cover developed, except for early Holocene climate anomalies. According to Dreibrodt *et al.* (2010), the general pattern is clearly reflected by the slope deposit record and at a closer look, there are different phases of variability within the record, and additional deposits are suspected to have been deposited during the Early Holocene. However, erosion and consequent deposition are fundamental for natural soil fertility maintenance in some areas, such as the Nile Delta, which receives sediments originating from Ethiopia. These natural processes have maintained soil fertility for centuries, but dam construction to control the Nile regime has disturbed this equilibrium (Ashman and Puri, 2002). Sediment from the Yellow River in northern China is also important for the maintenance of soil fertility on the adjacent floodplain (Fullen *et al.*, 1995). Currently, synthetic fertilizers can maintain soil fertility, and river floods pose serious risks to people on the alluvial plain. The more crucial recent problem is shoreline erosion at the Nile Delta mouth, which can cause severe problems for coastal settlements. The problems related to soil erosion are more evident when soil loss exceeds natural or geologic levels, usually due to the lack of soil conservation practices, which is called accelerated erosion (Selby, 1993). Geological soil erosion takes place under natural conditions (*i.e.*, without human disturbance) and does not usually cause major environmental problems, but accelerated soil erosion often does (Thornes, 1990; Gerrard, 1992; Selby, 1993; Morgan, 2005; Boardman, 2006; Boardman and Favis-Mortlock, 2014; Lopez-Vicente *et al.*, 2013; Almagro and Martinez-Mena, 2014; Labrière *et al.*, 2015). In the Holocene, usually little soil erosion occurs under natural vegetation cover. In most landscapes, while the vegetation is not removed, the export of matter occurs in the form of ions, with groundwater migrating into rivers and then transferring to the sea. Vegetation might be removed naturally by ageing and dying of trees in forests, but the resulting transfer of soil particles is within the distance of only several metres. Additional natural triggers are natural forest fires, from which one might expect a transfer of soil particles in the dimension of the specific slope. Severe climate changes (*e.g.*, glaciation) might result in deforestation, triggering erosion processes, on a hemispheric to global scale. Earthquakes can also trigger local soil erosion. In addition, humans often clear forests for economic purposes (usually for agriculture or timber extraction), which encourages soil erosion, since precipitation and snowmelt can then produce runoff and, in turn, detach and transport soil particles. One could describe such erosion as Anthropocene soil erosion; *i.e.*, the human imprint on the global environment is now so active that it rivals some of the great forces of nature in its impacts on the Earth system. In discussing the Holocene in Germany, Dreibrodt *et al.* (2010) commented that the comparison of the data from colluvial layers reflects the known settlement and land use history and testifies to the strong human impact on the geomorphologic system.

In the tropics, where rainstorms may be very intense, the signs of erosion are obvious, when the rivers become full of sediments, causing siltation (Selby, 1993; Fullen *et al.*, 1995; Goudie and Viles, 1997; Ashman and Puri, 2002; Fullen and Catt, 2004; Morgan, 2005; Boardman and Poesen, 2006; Guerra *et al.*, 2015; Labrière *et al.*, 2015). Labrière *et al.* (2015) pointed out that soil control is still provided in the humid tropics, to a certain extent, for crop and grass-dominated land uses, but is alarmingly depleted in bare soils, with dramatic consequences on soil loss. Even in temperate climatic zones, where heavy precipitation events are not usually as intense and concentrated as in the tropics, soil loss usually occurs at lower intensity, but also causes damage to agropastoral lands (Small and Clark, 1982; Abrahams, 1986; Parsons, 1988; Selby, 1993; Goudie, 1990, 1995; Guerra, 1994; Goudie and Viles, 1997; Ashman and Puri, 2002; Fullen, 2003; Morgan, 2005; Boardman and Poesen, 2006; Evans, 2006; Poesen *et al.*, 2006; Plaza-Bonilla *et al.*, 2013; Fullen and Catt, 2004; Labrière *et al.*, 2015). In addition, snowmelt, often over frozen and thus impermeable soil, can cause soil erosion in temperate zones.

Soil erosion also causes off-site problems, such as silting and pollution of areas where sediments are deposited, such as in rivers, reservoirs and lakes (Thornes, 1990; Wild, 1993; Goudie and Viles, 1997; Mosaddeghi *et al.*, 2009; Boardman and Favis-Mortlock, 2014; Nacinovic *et al.*, 2014; Guo *et al.*, 2015). According to Boardman and Favis-Mortlock (2014) the period when the soil is inadequately protected represents a window of opportunity for erosion. Thus, actual erosion in any year depends on: 1) the timing, amount and intensity of rainfall in that year, 2) the start date and duration of the "window of opportunity" and 3) the soil and morphological characteristics of the site.

The need for monitoring soil erosion with the use of experimental stations is very important, because through monitoring soil loss and runoff, erosion processes can be better understood. These important monitoring programs produce short-term data (sometimes for decades). Rare events (extreme erosion-low frequency, high magnitude precipitation events) might not be measured within such temporal limitations. The dataset could be extended immensely by the geomorphological study of historical soil erosion landscapes (Figs. 8 and 9). There are several ways to monitor and investigate soil erosion, in order to determine soil loss from fields and catchments. To do this, it is possible to use aerial photographs, over different months and/or years, to monitor rill and gully growth. When field and laboratory data, such as bulk density and total eroded area, are available, it is possible to calculate the amount of soil loss. This procedure is becoming more common, particularly when detailed scale aerial photographs are available. The use of remote sensing is another tool, which makes erosion studies more accurate and detailed, when combined with field and laboratory data. To achieve this aim, it is necessary to have good ground resolution (*i.e.*, ≤ 10 m). According to Morgan (2005), the studies of temporal changes in vegetation and soil conditions indicate that with further research it should be feasible to use remote sensing for continuous monitoring to identify in advance, when there is a high risk of erosion, so that appropriate protection measures can be implemented. In addition, depending on field conditions, monitoring programs and laboratory analyses, it should be possible to accurately determine how much soil is being lost from a specific field and/or catchment area.

Fig. 8 Aerial view of the Hilton Experimental Site, East Shropshire, England, UK, where soil loss and runoff have been monitored since 1982 (Fullen, 1992) (photo by Gill Barrett).

Fig. 9 Runoff plots at the Hilton Experimental Site, East Shropshire, England, UK (photo by Michael Augustine Fullen).

In 1960, the United States Department of Agriculture (USDA) established the maximum permissible value of 5 t ha^{-1} $year^{-1}$ of soil loss for the USA, which became known as the tolerable value (or T value) (Schertz, 1983). It is estimated that about 80% of the world's agricultural soils are subject to some form of erosion (Ashman and Puri, 2002). On average, soils form at a rate of about 1 t ha^{-1} $year^{-1}$. In Africa, Asia and South America, soil loss can exceed 30 t ha^{-1} $year^{-1}$; in Europe, where rains are not usually so intense, erosion rates can exceed 17 t ha^{-1} $year^{-1}$ (Boardman and Poesen, 2006).

Pressure on soils exerted by human activities is one of the main causes of erosion (Wild, 1993). The world population is large and growing, and totaled 7 401 421 170 according to the world population clock (Worldometers Info, 2016). The exact world population is unknown; this is the best estimate we have, based on the integration of several demographic models. Moreover, people understandably aspire to higher living standards, placing yet more pressure on soil resources. These demographic processes require larger areas to cultivate, graze cattle and provide timber for fuel and construction. Together these activities clear permanent natural vegetation and expose soils to the erosive processes of wind and water. Although soil erosion occurs in different parts of the world, there is a difference between small fields, used by local farmers for subsistence agriculture, and the large fields of agroindustrial monocultures, since the latter usually use large connected fields. These often have poor soil structures and low soil organic matter contents, which produce much more runoff, and consequently, much more erosion. This is the Brazilian case, where these conditions produce total soil losses > 50 t ha^{-1} year^{-1}, and sometimes > 100 t ha^{-1} year^{-1} (Manzatto *et al.*, 2002; Guerra *et al.*, 2014). Wild (1993) summarized the main causes of erosion as 1) vegetation clearance, leaving soils unprotected; 2) agriculture and cattle ranges, without conservation practices; 3) cultivation and cattle ranges on slopes, sometimes $> 45°$, without conservation practices; 4) trails caused by animals and humans, compacting soils and thus increasing surface water flow; 5) highway construction, with inadequate environmental planning, which increases surface water flow and thus generates rills and gullies and 6) different types of mineral quarries and other economic activities, leaving soils unprotected, and without proper rehabilitation, during and at the end of these activities. Many researchers (*e.g.*, Selby, 1993; Goudie, 1995; Goudie and Viles, 1997; Favis-Mortlock and Guerra, 1999; Ashman and Puri, 2002; Fullen and Catt, 2004; Morgan, 2005; Valentin *et al.*, 2005; Boardman, 2006; Evans, 2006; Boardman and Favis-Mortlock, 2014; Monsieurs *et al.*, 2015) agree with Wild (1993).

Despite being a typical geomorphological process from rural areas, Guerra and Hoffmann (2006) outlined that for two Brazilian cities (São Luis Municipality, Maranhão State and Palmas Municipality, Tocantins State), although they were founded in different periods (São Luis Municipality in the 17th Century and Palmas Municipality in the 20th Century) and although they have different locations, histories and climates, both cities are experiencing an increasing problem of gully erosion, especially within the city limits (Guerra and Hoffmann, 2006). This is due to similar factors, including vegetation clearance, lack of urban planning, inadequate rain and sewage systems and unpaved roads, especially on the city outskirts, which is confirmed by several studies on gully erosion within urban areas (*e.g.*, Selby, 1993; Goudie and Viles, 1997; Favis-Mortlock and Guerra, 1999; Poesen *et al.*, 2003; Morgan, 2005; Boardman, 2006; Evrard *et al.*, 2010; Graeff *et al.*, 2012; Monsieurs *et al.*, 2015).

Besides the need to implement soil conservation practices (Mishra *et al.*, 2015) to avoid damage to both the soil and environment, it is necessary to apply different techniques to recuperate soils once they become degraded (Fullen *et al.*, 1995; Fullen and Catt, 2004; Bhattacharyya *et al.*, 2009; Rodrigues and Bezerra, 2010; De Baets *et al.*, 2011; Fullen *et al.*, 2011; Bhattacharyya *et al.*, 2012; Dhital *et al.*, 2013; Guerra *et al.*, 2015). Some parts of the world produce the highest erosion rates due to soil mismanagement practices, such as slash and burn, and the absence of appropriate soil conservation techniques (*e.g.*, terracing, contour cultivation and crop rotation) (Fullen and Catt, 2004; Morgan, 2005; Labrière *et al.*, 2015). Consequently, long-term spatial variations in erosion occur in relation to changes in land cover, *i.e.*, soil use and management. According to Bhattacharyya *et al.* (2012), vegetation growth on problematic slopes often encounters problems, such as the absence of initial binding material in the soils prone to erosion by water.

Biological geotextiles constructed from different materials, such as buriti (*Mauritia flexuosa* L.) in Brazil, are readily available in São Luis Municipality, and are simple and cost-effective to manufacture and provide immediate erosion control (Guerra *et al.*, 2015) (Figs. 10 and 11). Most examples of soil recuperation are very much localized and have short-term data. Hence, long-term data showing the effectiveness of land recuperation at the drainage basin scale are still needed (Kerr, 1998; Fullen and Catt, 2004; Morgan, 2005; Bhattacharyya *et al.*, 2009, 2012; Guerra *et al.*, 2014). Very good results have been obtained in São Luis Municipality using leaves of buriti, a typical palm tree from Maranhão State, where the geotextiles plus vegetation cover have decreased runoff and erosion, consequently promoting water circulation within the soil profile (Guerra *et al.*, 2015). The runoff which forms the gully is produced completely within the catchment area above the gully head, and at this specific site, the catchment area is very small because the local authorities have made major urban works to decrease this area. Consequently, little runoff is now generated. Therefore, the recuperation using buriti leaves has worked very well. Although there are many examples of soil recuperation, most of them are considered on a local scale and one has to also consider erosion on a global scale. Even considering soil erosion as a global problem of Anthropocene soil erosion, local studies might contribute, in the long-term, to solving this problem, or at least to decreasing soil loss and promoting sustainable agriculture. This is the case of many countries, but especially those where agricultural production is crucial to development and the majority

Fig. 10 Recuperation work in Sacavém Gully, São Luis Municipality, Maranhão State, Brazil, in February 2008, with the application of buriti geotextiles, manure and grass seeds (photo by José Fernando Rodrigues Bezerra).

Fig. 11 Gully wall completely recuperated in Sacavém Gully, São Luis Municipality, Maranhão State, Brazil in February 2008, with the application of buriti geotextiles, grass seeds, manure and nitrogen, phosphorus and potassium fertilizers (photo by José Fernando Rodrigues Bezerra).

of the rural people base their livelihood strategies on the primary sector (Kerr, 1998). This is only one example of how geotextiles made from vegetal fibres can be used to recuperate eroded slopes. They are usually cheaper than synthetic geotextiles and generate income for impoverished local people. Soil erosion processes are influenced by many factors, including rainfall, soil properties, land use and land management. Therefore, decreasing surface runoff in the catchment area (*e.g.*, by increasing soil infiltration capacity and evapotranspiration rates) results from a permanent vegetation cover. Consequently, the fixation of gully walls is a real erosion mitigation action and, in many circumstances, it only attenuates the erosion processes. There are many soil conservation practices, including mulching, crop rotation systems, no-tillage agriculture, terracing and contour cultivation. Examples of effective soil conservation practices include: 1) increased extent and density of vegetal cover; 2) use of green manure (*i.e.*, the addition and incorporation of undecomposed vegetal biomass on fallow soils); 3) good soil management practices, particularly minimum tillage; 4) maintaining of soil cover, especially retaining of harvest residues on topsoil, thus adding organic matter to soil systems; 5) improved cattle management systems and optimized combination of these systems with arable cropping systems to minimize soil erosion; 6) reafforestation, particularly protection of riparian vegetation, on erodible soils; 7) contour cultivation, which has shown to reduce runoff by $\leq 30\%$ and soil loss by $\leq 50\%$ in experiments in Brazil (Bertoni and Lombardi Neto, 1990); 8) vegetative buffers (strips of vegetation) in agricultural areas, which act as physical barriers to runoff and erosion and encourage infiltration; 9) strips of stones in agricultural areas, where stones are placed in small channels dug parallel to contours, to impede surface water flow and 10) construction of small retention basins in small depressions between areas of permanent agriculture. All these conservation practices have promoted sustainable agriculture in several parts of the world, which improves soil drainage and simultaneously decreases soil erosion. Nevertheless, in many areas, soil degradation still occurs because of the use of conventional agricultural systems and cattle ranching (Fullen and Catt, 2004; Morgan, 2005; Goudie and Boardman, 2010; Guerra *et al.*, 2014).

APPROPRIATE REMEDIAL BIOENGINEERING METHODS AND THE POTENTIAL OF THE MEASURES

The role of the main environmental triggers and human actions on slopes nearly always accelerate mass movement. The unplanned growth of cities is an important factor triggering mass movement. When this occurs often, damage is severe and may even cause fatalities. Soil erosion is another form of land degradation on slopes. Depending on the interactions of different erosion factors, including natural ones and soil use and management, different soil features appear on the soil surface, including sheet, rill and gully erosion. Although these erosion features tend to be more dramatic in the tropics, in recent decades they have also occurred in temperate morphoclimatic regimes. Wherever they occur, there is always damage and losses to agriculture and grazing land, with concomitant financial costs. The Holocene encompasses the growth and impacts of the human species world-wide, including all written history, the development of major civilizations, and the overall significant transition toward urban living in the present. Human impacts on modern-era Earth and its ecosystems are considered to be of global significance for the future evolution of living species, including concomitant lithospheric or, more recently, atmospheric evidence of human impacts. Holocene mass movement and soil erosion are global problems, as they cause damage and deaths. These problems also make life more difficult for millions of people, especially the poorest ones, who suffer most with the effects of catastrophic landslides in urban areas and soil erosion in agricultural fields. According to Borgatti and Soldati (2010), establishing links between climate and past landslides activity is indeed very difficult. This is primarily due to the few records of landslide events (imprecise dates, incomplete databases) dating back to the last century, to the Little Ice Age and to the Holocene. Both mass movement and soil erosion, although two different forms of land degradation, usually cause severe forms of environmental damage and material loss and even injury and death. Both cause on-site and off-site effects, causing problems to where they occur (the export zone) and to places of deposition (import zone). The distance between export and import zones can be many kilometres. Preventive way of handling these very destructive geomorphological processes is always the best way to address them (*i.e.*, "prevention is better than cure"). When preventing soil erosion and mass movement, one has to also consider the role of climate change, with most predictions suggesting more intense and extreme rainfall. Together with population growth, this can drastically increase landslides and soil erosion, especially in developing countries, where both population and agricultural pressure on land resources often lead to exploitation of unstable slopes (Borgatti and Soldati, 2010). Nevertheless, once such environmental damage occurs, it is possible to recuperate affected areas. The use of geotextiles has been adopted in many countries, such as in Brazil, using vegetal fibres sourced from indigenous vegetation and local labour and knowledge. This has potential as a sustainable way of tackling the problems of degraded areas.

CONCLUSIONS

Soil erosion and mass movement are the products of complex interactions between rainfall regime, soil properties, slope characteristics, vegetation cover and land use and management. Their interaction often produces excessive erosion rates. Understanding soil erosion and mass movement as geomorphological processes is an essential step towards developing effective soil conservation strategies. There is a close association between soil classes in Brazil and soil erodibility. Field measurements suggest that erosion rates often far exceed tolerable levels and thus impair the ability of soil systems to sustainably produce crops. The same applies to mass movement, especially in cities, where inadequate construction can lead to catastrophic geomorphological processes, causing hundreds of fatalities and severe damages to urban infrastructure. Carefully designed preventative and remedial measures in urban and peri-urban areas can decrease the frequency and magnitude of these problems. Current research in applied urban geomorphology is progressing the development of effective slope stabilization and soil conservation protocols.

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