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Strategies for Linear Erosion Control in Tropical and Subtropical Environments

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A B S T R A C T

Rills, ravines, and gullies are erosion features commonly associated with concentrated runoff, impacting agricultural lands and watercourses in agroecosystems and natural environments. The objective of this paper was to provide a comprehensive literature review on linear erosion features and control techniques applied in tropical and subtropical regions. This review has a narrative literature approach and explores stream characteristics, gully formation and development and control measures, delineating their relevance and the state-of-the-art. The paper also examines the interplay between linear erosion and sediment dynamics, emphasizing how pronounced erosion in specific areas contributes to substantial land displacement and alterations in streambed morphology. Notably, it evaluates various methods of linear erosion control tailored to tropical and subtropical climates, categorizing strategies into two groups: general techniques for soil and water conservation and measures specifically designed for areas affected by concentrated flow, irrespective of apparent erosive processes. Among the effective practices highlighted are terracing, contour farming, the implementation of vegetative barriers, check dams, and the adoption of soil tillage systems characterized by minimal or no disturbance, such as minimum tillage and no-tillage. These practices have demonstrated efficacy in mitigating surface runoff and reducing sediment yield.

Keywords: Gully formation, erosion control techniques, Soil and water conservation.

Estratégias para o Controle de Erosão Linear em Ambientes Tropicais e Subtropicais

RESUMO

Sulcos, ravinas e voçorocas são formas de erosão comumente associadas ao escoamento concentrado, impactando áreas agrícolas e cursos d’água em agroecossistemas e ambientes naturais. Este trabalho teve como objetivo realizar uma revisão de literatura compreensiva sobre as feições de erosão linear e as técnicas de controle aplicadas em regiões tropicais e subtropicais. A revisão adota uma abordagem narrativa, explorando as características de drenagem, a formação e o desenvolvimento de voçorocas e as medidas de controle, destacando sua relevância e estado da arte. O artigo também analisa a interação entre erosão linear e a dinâmica dos sedimentos, enfatizando como áreas com erosão intensa contribuem para grandes deslocamentos de solo e alterações significativas na morfologia dos leitos dos cursos d’água. Adicionalmente, são avaliados métodos de controle da erosão linear adaptados aos climas tropicais e subtropicais, categorizando as estratégias em dois grupos: técnicas gerais de conservação do solo e da água e medidas específicas para áreas afetadas pelo fluxo concentrado, independentemente da manifestação de processos erosivos aparentes. Entre as práticas eficazes destacadas estão o terraceamento, o cultivo em nível, o uso de barreiras vegetativas, barragens de sedimentação e a adoção de sistemas de preparo do solo que minimizem ou eliminem a mobilização, como o cultivo mínimo e o plantio direto. Essas práticas têm demonstrado eficácia na redução do escoamento superficial e da produção de sedimentos.

Palavras-chave: Formação de voçorocas, técnicas de controle da erosão, conservação do solo e da água.

Introduction

Anthropogenic erosion stands as one of the most pressing soil degradation issues, with land-use changes over the past three centuries aggravating this problem globally (Poesen et al., 2018). Regions characterized by high precipitation rates, notably humid areas, are especially susceptible to intensified erosive processes (Oliveira et al.; 2010; Labrière et al., 2015).

The effects of erosion are manifold. Locally, it compromises soil's physical, chemical, and biological properties, resulting in nutrient depletion and even rendering arable land unproductive (Holz & Augustin, 2020). On a broader scale, erosion leads to siltation and contamination of dams, channels, and water bodies (Li & Fang, 2016). Moreover, sediment deposition stemming from erosion can disrupt ecosystems and alter river and coastal morphology and dynamics, causing severe environmental consequences (Kuhn et al., 2023). Environmental factors, particularly intense rainfall, can exacerbate this process, inflicting substantial environmental harm (Souza et al., 2014; Dechen et al., 2015).

Two primary forms of anthropogenic soil erosion are discernible: sheet erosion and linear erosion. Sheet erosion predominantly occurs in agricultural fields (Pimentel & Burgess, 2013), where rainfall dislodges particles from exposed soils, subsequently carried away by uniform and shallow water flow across the soil surface (Falcão et al., 2020; Ni et al., 2019). Conversely, linear erosion occurs in areas characterized by concentrated surface runoff facilitated by topographical and soil characteristics (Dube et al., 2020), manifesting as rills, ravines, or gullies (Almeida Filho, 2014; Velasquez & Righes, 2019).

In this context, there is a compelling need to research and develop efficient techniques tailored to tropical and subtropical regions, considering their varied results under different circumstances. However, a notable gap exists in the literature concerning techniques for controlling linear erosion and their efficacy (Castillo & Gomez, 2016). Therefore, the objective of this paper was to provide a comprehensive literature review of linear erosion control techniques applied in tropical and subtropical regions.

Methodology

Understanding the formation processes and developmental phases of various linear erosion features is essential for developing strategies to prevent, control, and restore degraded areas. A lack of knowledge about environmental, pedogenetic, and geomorphological conditions can increase the failure rates of these techniques, causing losses in rural areas and tragedies in urban areas.

The strategies in this article are categorized into two sections: the first addresses common soil and water management and conservation techniques in order to reduce the energy of surface runoff in vulnerable regions to linear erosion; the second category focuses on specific techniques for areas with concentrated surface flow and/or active erosive processes.

This study was developed as a narrative literature review, primarily based on discussion on the linear erosion processes in order to support ongoing scientific research on the suitable techniques to prevent or control such events.

To deepen the theoretical foundation, an additional literature search was conducted, utilizing articles and other works published in indexed journals, accessed through platforms such as Google Scholar (http://scholar.google.com) and Periódicos CAPES via Comunidade Acadêmica Federada – CAFe (https://www.periodicos.capes.gov.br/index.php/acesso-cafe.html). The research focused on tropical and subtropical environments. Books, manuals, technical bulletins, and circulars from universities and research institutions were also consulted, although the priority was given to peer-reviewed scientific published papers in indexed journals.

The main used keywords in the searching: "soil erosion," "linear erosion," "rill" and "rills," "ravine" and "ravines," "gully" and "gullies," "gully development," "erosion control," "gully reclamation," "soil conservation practices," "soil conservation measures," "geotextile," and "soil bioengineering," among others and their combinations."

Rills, ravines, and gullies

Rill erosion refers to shallow linear channels, typically ranging from 0.02 to 0.2 meters in depth (with a maximum limit of 0.5 meters), formed exclusively by concentrated surface runoff in depressions on the soil surface during or immediately after rainfall (Imeson & Kwad, 1980; Thomaz, 2013; Ou et al., 2021). Rills may form interconnected networks (Shen et al., 2015) but are typically eradicated from the soil surface through tillage and do not reappear in the same location after subsequent rainfall events (Foster, 1986).

Ravines, with size between rills and gullies, exhibit depths exceeding 0.5 meters. These erosional features are typically unbranched, and the absence of groundwater emergence distinguishes them from gullies (Lafayette et al., 2011). Ravines commonly display a V-shaped cross-section (Kuhn et al., 2023), with more pronounced development in depth than in width.

Gullies are persistent linear erosional features characterized by a depth exceeding 0.5 meters and significant soil loss at the head (upper vertical limit of the feature), which remains unaffected by soil tillage (Thwaites et al., 2022). These features can attain substantial dimensions, with depths ranging up to 20–30 meters, contingent upon the flow of both surface and subsurface waters (Vanmaercke et al., 2021; Roberts et al., 2022).

Generally, the dominant erosive mechanism within gullies is mass movement along the sidewalls and headcut retreat, either with or without weakening due to infiltration, progressively enlarging the feature's extent (Cândido et al., 2020; Gao et al., 2021). The development of gullies is influenced by flow dynamics associated with rainfall within both the gully channel and its catchment area, exerting a profound impact on their development (Thwaites et al., 2022).

The gullies are mainly classified in two primary types: ephemeral and permanent (Poesen et al., 2003; 2018; Liu et al., 2021; Frankl et al., 2021). Ephemeral gullies are shallow enough to be eradicated through soil tillage and may reappear in the same location following subsequent surface runoff events, unlike rill erosion. Consequently, the most favorable conditions for ephemeral gully formation typically arise after soil tillage for sowing (Capra, 2013). Conversely, permanent gullies are channels too deep to be eliminated by conventional tillage practices, often reaching depths ranging from 0.5 to 30 meters (Poesen et al., 2003).

The nomenclature and definition of linear erosion features remain controversial due to regionalized approaches, although efforts such as those by Thwaites et al. (2022) aim to unify them. These definitions and nomenclatures are essential as they summarize the characteristics and conditions related to the linear erosion feature to be controlled, as well as the factors that originated it, a topic to be addressed in the next section. In this work, we have chosen to maintain the nomenclature commonly used in Brazil. However, the information and results presented here can be appropriately extrapolated to other tropical and subtropical regions.

Processes driving linear erosion and development

To understand the mechanisms underlying the formation of linear erosion features, it is essential to introduce two important concepts associated with soil erosion. The first concept refers to erosivity, which is linked to water dynamics, while the second concerns the soil's passive role in this process, known as erodibility (Freires et al., 2023).

Erosivity denotes an index quantifying the force of rainfall capable of inducing soil loss. It is typically computed by multiplying the energy of rainfall by the volume of precipitation (Nearing et al., 2017). Projections indicate that in the forthcoming years, approximately 80-85% of the Earth's surface performs an increase in rainfall erosivity attributable to climate change, and this escalation is expected to surpass 30% by 2050 and exceed 35% by 2070 (Panagos et al., 2022).

In the context of the Universal Soil Loss Equation (USLE) and its subsequent revisions (RUSLE and RUSLE2), erodibility refers to the susceptibility of soil to erosion, representing the passive component of the erosion process. It can be estimated through various indicators, such as aggregate stability (Nciizah & Wakindiki, 2015), or more traditionally, through field experiments conducted on plots under fallow conditions. These experimental plots typically have a length of 22.1 meters and a slope of 9%, as specified by Wischmeier and Smith (1978).

In fragile soils, the erosion process start with intense rainfall and surface runoff, characterized by sufficient volume and energy to induce soil disaggregation, surface sealing (mainly in bare soils), and sediment transport (Chaplot, 2013; Wei et al., 2019). Rainfall intensity, defined as the volume of rain per unit of time, must exceed the soil's water infiltration rate, or the soil must already be saturated due to previous rainfall events (Carvalho et al., 2015; Wang et al., 2015). Additionally, slope plays a remarkable role in this process by imparting speed and energy to surface runoff, while topographic features, relief, and geomorphology delineate zones of concentrated water flux that may initiate linear erosive processes (Valentin et al., 2005).

Generally, the characteristics of linear erosion stem from the concentration of surface runoff, leading to soil shear and subsequent sediment transportation, along with subsurface flow facilitated by the formation of subsurface and underground channels, known as soil piping (Dube et al., 2020; Bernatek-Jakiel & Poesen, 2018). Soil piping may arise from a sudden decrease in infiltration rate due to a less permeable soil layer, enabling high lateral subsurface flow, or through the activities of soil fauna and root decomposition, creating tunnels that enhance subsurface water flow and increase in diameter over time (Chaplot, 2013).

As previously discussed, rills are erosional features exclusively formed through the concentration of surface runoff (Imeson; Kwad, 1980). The emergence and evolution of rills are influenced by factors such as the frequency of high-intensity, short-duration precipitation events, the length and slope of the ramp, surface soil roughness, and tillage practices (He et al., 2016; Qin et al., 2018). Considering that ravines are an erosion type with a vertical incision greater than rills, they are primarily favored by the presence of less consolidated material or soil that allows the deepening of the feature. This is why ravines generally have a "V"-shaped cross-section (Kuhn et al., 2023).

As a linear erosion process, gullies may suddenly appear during extreme rainfall through soil mass movement or gradually (Valentin et al., 2005; Rahmati et al., 2022). Regardless of their origin, mass movement dominate the development of gullies, driving expansion both vertically through headcut retreat and laterally (Cândido et al., 2020).

As noted by Frankl et al. (2021), gullies typically undergo a “cut and fill” cycle, naturally spanning 50 to 100 years for completion. During the cutting phase, rapid headcut development and channel degradation occur, rendering cross-sections and headcuts more susceptible to instability due to shear stress. Control during this phase is challenging and requires complex and costly techniques. As the longitudinal profile evolves, the headcut recedes, resulting in a gentler slope, and the headcut advances to the filling phase. During this phase, aggradation and stabilization of the lateral banks predominate, creating favorable conditions for vegetation development due to the higher presence of sediments and nutrients. This allows the use of more accessible and straightforward techniques for gully control (Lanckriet et al., 2015; Leenman & Tunnicliffe, 2018; Frankl et al., 2021).

Linear erosion and its relation with sediment dynamics

One of the most widely recognized methods for estimating soil loss is the Universal Soil Loss Equation (Eq. 1). There have been advancements in this model, known as the Revised Universal Soil Loss Equation - RUSLE and RUSLE2. These equations are presented and detailed in Wischmeier & Smith (1978), Renard et al. (1997), and USDA-Agricultural Research Service (2013).

$$A = R \times K \times L \times S \times C \times P \quad \text{(Eq. 1)}$$

Where: A = annual average erosion (mass area-1 year-1) for the slope length; R is the erosivity factor (erosivity area-1 year-1); K = soil erodibility factor (mass (erosivity unit)-1); L = slope length factor (dimensionless); S = slope steepness factor (dimensionless); C = soil cover factor (dimensionless); and P = support practice factor (dimensionless).

In general, the USLE and its revised models only quantify sediment production from surface erosion. Other techniques should be employed to quantify sediments produced in gullies and ravines (Alewell et al., 2019). In the latter case, the amount of sediment can be estimated, for example, through direct field assessments (Liu & Liu, 2020) or by using digital terrain and elevation models (Zhang et al., 2018).

A study in Southeastern Brazil, revealed that over six months, sheet erosion accounted for a sediment production of merely 2.11 m³, and in contrast, rill and gully erosion produced significantly higher volumes of sediment, measuring 5.69 m³ and 63.39 m³, respectively (Cândido et al., 2020). Similar results were observed in subtropical areas in a small watershed in southwestern China, where Zhang et al. (2018) showing a low contribution of sheet erosion to total sediment production (< 18.66%). Conversely, gully erosion was the dominant soil degradation process in the region. In another study also in China, Liu and Liu (2020) noted that in a small watershed predominantly composed by Ultisols with granitic parent material, gully erosion was the main contributor to sediment (52% of production) compared to other erosion types.

Steeper slopes facilitate faster water movement, which can lead to more severe concentrated erosion (Romano et al., 2018). This is because concentrated surface flow exhibits greater erosive hydraulic force and higher sediment transport capacity than the more dispersed flow resulting from sheet erosion (Qin et al., 2018). Despite linear erosive processes producing a high sediment load, the predominance of one erosive process over the other depends on factors such as land use, slope, erodibility, and the predominant intensity of raifall in a given region or watershed (Zhao et al., 2022). In Mexico, Everard et al. (2013) evaluated that most sediments originated from agricultural areas, although they found such variation of sediments sources like sediment contributions from gullies, pastures, and farming areas.

The distances of sediment transport depend on the type of erosive process as well as environmental factors such as topography, land use, soil surface roughness, and characteristics of surface runoff. In general, the main factors controlling the processes of sediment disaggregation, transport, and deposition are the speed of surface runoff and the particle size (Hajigholizadeh, Melesse e Fuentes, 2018). According to Poesen (2018), minimum sediment transport distances are less than 1 meter for disaggregation caused by the splash effect (soil disaggregation produced by the impact of raindrops on the soil surface); less than 100 meters for sheet erosion, rill erosion, piping erosion, and explosion craters; less than 1 km for ephemeral gullies; and more than 1 km for sediment export from gully basins. In storm events in subtropical regions, erosion sediments can be transported up to 70 km (Yang et al., 2023).

As previously mentioned, the production and export loads of sediments by linear erosion processes are very important and impact the environment as well. Therefore, erosion control methods must be adopted not only to mitigate the effects of soil loss in the directly affected area but also to reduce the reception of sediment loads impacting other areas and watercourses.

Methods for controlling linear erosion in tropical and subtropical climates

The selection of erosion control techniques should be tailored to the specific environmental characteristics in any considered region. For instance, tropical and subtropical zones typically exhibit average annual temperatures exceeding 18 °C and 10 °C, respectively, and commonly experience annual rainfall levels surpassing 1,000 mm (Remedio et al., 2019). These regions are characterized by diverse soils, predominantly very weathered, with kaolinitic clays and/or oxides (iron and aluminum), mostly clayed soils, and soil fertility ranging from low to extremely low (Zaroni & Santos, 2021).

In tropical regions, combinations of high temperatures and heavy rainfall, coupled with improper soil management, exacerbate various erosive processes (Flores et al., 2020). Excessive soil disturbance, which destroys soil structure, lack of vegetation cover, downhill planting to the slope, poorly planned rural roads, and the absence or simplification of crop rotation deplete the quality of tropical soils (Wantzen & Mol, 2013). One direct indicator of this decline is the reduction in soil organic matter levels (Lal, 2015). To reverse this trend, it is essential to adopt less impactful tillage practices. These include minimizing soil disturbance, maintaining or increasing vegetation cover, enriching the soil with organic matter, and properly planning land use on farms by adopting soil and water conservation techniques (Adeli et al., 2020).

Such practices mitigate splash effects, favor greater water infiltration, and reduce surface runoff (Labrière et al., 2015). Ultimately, controlling linear erosive processes can be achieved by applying soil and water conservation techniques or through targeted measures in areas of concentrated surface runoff (Filizola et al., 2011).

Mechanical and vegetative soil and water conservation techniques

Terracing is a long-established and widely used practice for soil and water conservation worldwide (Back & Wildner, 2012; Wei et al., 2016). A terrace is a soil-built structure consisting of a channel and a dike (Figure 1). Its function is to contain surface runoff from the area above the terrace, ensuring proper water infiltration into the soil. Before implementing terraces, a preliminary study of the area is necessary to identify soil characteristics, slope, and land use, which will determine the type, base width, and spacing between terraces (Pasini et al., 2017; Bassani et al., 2023).

Figure 1. Terrace (on the left), retention basin (in the center), and a combination of both (on the right) installed in an Argisol in the municipality of São Cristóvão, Northeastern Brazil.

Terracing primarily serves to control erosion and reduce surface runoff. However, these structures also enhance groundwater recharge, increase nutrient availability in the soil, and promote biomass accumulation (Wei et al., 2016). Furthermore, terraces can significantly reduce surface runoff and sediment transport by 41.9% and 52%, respectively (Deng et al., 2021). This reduction in runoff and sediment loss positively impacts agricultural productivity, as the slowed runoff increases soil moisture content and extends water availability, which are critical factors for crop growth and health (Londero et al., 2018).

Terraces can be categorized based on their functions: infiltration terraces, also known as level terraces, are designed to maximize water absorption into the soil, while gradient terraces are constructed with a slight slope to facilitate controlled water runoff (Duan et al., 2021).

The use of retention basins (Figure 1) serves as a conservation strategy designed to mitigate surface runoff from areas outside agricultural lands, particularly roads. Also called catchment basins are excavated structures in the soil built to receive runoff from external areas, slowly storing and infiltrating the received water (Dadalto et al., 2016). Forest roads can concentrate rainwater flow, leading to accelerated soil erosion, especially in areas with steep slopes (Kastridis, 2020). Generally, these structures are installed along the margins of rural roads, dividing the road into segments to eliminate the cumulative effect of runoff and considering the area and slope of the road as well as the maximum 24-hour precipitation in the area (Silva et al., 2014).

Cunha et al. (2013) observed positive results when techniques were combined, such as the expansion of terraced areas on slopes, promotion of environmental education, road repairs, and the construction of “Barraginhas” (small dams for drainage of unpaved roads). These measures significantly reduced soil loss, from 2.35 to 1.78 tons per hectare per year (approximately 25%) (Mamedes et al., 2023).

Among the most common vegetative soil conservation techniques, contour planting or sowing is widely utilized (Santos et al., 2010; Borges et al. 2014; Han et al., 2020; Zhang & Wang., 2021; Molla et al., 2022). Its goal is to position crop lines perpendicular to the slope, acting as barriers against surface water runoff and sediment. It is often employed in conjunction with other conservation techniques such as crop rotation, no-till farming, and terracing (Marioti et al., 2013).

Eduardo et al. (2013) conducted an evaluation of corn plots in a Red-Yellow Latosol under natural rain conditions in Rio de Janeiro state, Brazil. They observed that contour sowing led to a 50% reduction in soil loss compared to downhill cultivation. Similarly, Carvalho et al. (2015) simulated rains on corn plots under conventional tillage and found that contour sowing resulted in the lowest cumulative soil losses in the experiment.

Vegetated barriers are soil and water conservation structures consisting of level strips composed by perennial species (Figure 2). Their main purpose is to contain surface runoff and enhance water infiltration rates (Silva, 1995). Similar to terraces, these plant barriers is installed to divide the length of the slope. They reduce sediment transport between areas and distribute surface runoff, thereby diminishing the occurrence of peaks that promote linear erosion. Additionally, these structures create ecological corridors, facilitating the movement of fauna and flora between native or regenerated areas while also offering protection against wind erosion (Barrientos-Pérez et al., 2023).

Kumar et al. (2023) analyzed vetiver grass (*Chrysopogon zizanioides*) and other grasses, their growth and root architecture, and vetiver exhibited the highest root area ratio, the maximum soil cohesion, indicating greater resistance to runoff across all soil mixtures tested. Soil Bioengineering techniques, such as vetiver grass contour lines, have demonstrated effectiveness in safeguarding the banks of the São Francisco River in Sergipe state, northeastern Brazil. These contour lines were meticulously laid out using georeferencing methods and then planted along the transects, which were delineated following the riverbank concavity (Holanda et al., 2021).

Figure 2. Vegetated barriers and the root system of *Chrysopogon zizanioides* (Vetiver grass) in the municipality of Amparo de São Francisco and São Cristóvão, Northeastern Brazil.
Source: The authors

Similar to terracing, vegetated barriers play a crucial role in drier regions by not only controlling surface runoff rates and sediment transport but also maintaining optimal soil moisture levels conducive to crop development and productivity. In the arid region of Karnataka, India, Balooragi et al. (2022) observed that vegetative barriers constructed with *Pennisetum hohenacker* and *Chrysopogon zizanioides* resulted in higher soil moisture levels (15.28% and 13.84%, respectively) compared to the control treatment (12.08%). A similar outcome was reported in northeastern Brazil by Montenegro et al. (2019) using vegetated barriers of prickly pear (*Opuntia cochenilifera*) spaced at 0.1 x 1.5 m.

In the subtropical region of Punjab, India, Singh et al. (2017) found that vegetative barriers comprised of vetiver (*Chrysopogon zizanioides*), *Eulaliopsus purpureum* x typhoides, and *Saccharum munja* significantly reduced surface runoff and soil loss while ensuring higher yields of various crops (corn, sesame, mung bean, wheat, mustard, and lentil). Similarly, in Ethiopia, Mekonnen et al. (2016) evaluated vegetative barriers 1.5 m wide with various species (*Pennisetum pedicellatum*, *Hyparrhenia rufa*, *Pennisetum schimpri*, *Eleusine floccifolia*, and Vetiver grass) on an 8% slope and found that *Pennisetum pedicellatum* had higher sediment storage efficiency (76%).

Soil management systems, also referred to as cropping systems, encompass a range of techniques employed to prepare soil for agricultural cropping systems. Depending on the utilized technologies, these practices can create either favorable or unfavorable conditions for crops and soil conservation (Silva & Mielniczuk, 1998). As emphasized by Hirakuri et al. (2012), the term "cropping systems" encompasses a broader context, including not only conventional soil management practices but also considerations such as planning, soil fertility management, cultivar selection, phytosanitary control practices, and harvesting and post-harvest processes. Therefore, in this study, the term "soil tillage system" is chosen to be used more frequently including conventional tillage, minimum tillage, and no-tillage. Conventional tillage involves practices often characterized by excessive soil disturbance (Peng et al., 2023), which can be particularly detrimental to tropical and subtropical soils (Brown et al., 2018). This system typically includes plowing and harrowing phases (Carvalho Filho et al., 2007).

Conservation tillage systems (Figure 3) have emerged to mitigate the impacts of conventional tillage, with a focus on minimum tillage and no-till. Minimum tillage works to reduce soil mobilization by either decreasing operations or minimizing soil disturbance (Didoné et al, 2014). No-till, on the other hand, seeks to eliminate soil mechanization (Acosta et al., 2014; Passos et al., 2018; Silva et al., 2021).

Figure 3. (a) No-till system, (b) minimum tillage, and (c) conventional tillage in Sergipe state, Northeastern Brazil.
Source: The authors

Huang et al. (2022) observed that minimum tillage showed high efficiency in reducing soil loss in studies conducted in the subtropical region of Asia. Generally, the no-till system maintains higher concentrations of organic carbon, acting as a cementing agent and resulting in larger and more resistant aggregates, which significantly enhance soil erosion resistance (Loss et al., 2017; Sales et al., 2017).

Direct prevention and control techniques for managing concentrated flow and linear erosion features

Generally, linear erosion features with a depth of less than 0.5 meters can be mitigated with conventional soil tillage (Mamedov & Levy, 2019). However, this soil management practice is primarily related to land mechanization for agricultural use and one of the direct impacts of erosion processes is the reduction of the soil surface layer thickness due to continuous soil loss (Liu et al., 2013; Silva et al., 2015; Heri-Kazi & Bielders, 2021).

It is often mentioned that linear erosion cannot be simply “erased” with the use of soil tillage implements but requires soil and water conservation techniques. Without these strategies, erosion recurrence is likely. In cropped areas, it is noteworthy that some linear erosive features reappear in natural drainage channels and are considered ephemeral, capable of being covered again with each periodic tillage (Douglas-Mankin et al., 2020; Liu et al., 2021).

Working with soil and water conservation techniques upstream and around linear erosion features directly reduces the speed and energy of concentrated surface runoff (Zhang et al., 2019). Consequently, this mitigation in flow dynamics significantly decreases the potential for further erosion and sediment transport. Thus, the erosive process can be reduced or even interrupted, diminishing the occurrence of rills, ravines, and gullies (Machado et al., 2010). In this regard, Barros et al. (2018) discovered that introducing *Eucalyptus* sp. fields along with soil conservation practices around gullies decreased the evolution and expansion of these erosive processes. However, vegetative barriers have vulnerabilities, mainly due to vegetation deterioration over time (Albert-Belda et al., 2019). In such cases, gaps left by dying plants create preferential pathways for surface runoff, initiating linear erosion processes.

Diverting concentrated surface runoff can protect vulnerable areas from linear erosion (Boardman et al., 2019) and may be an initial measure for gully control (Andrade et al., 2005). However, improper diversion can trigger new erosion occurrences. It is generally recommended to divert runoff towards areas with native vegetation or areas with low slopes and low risk of erosion. Amangabara (2014) discovered that improper surface water diversion from roads led to gully and ravine formation in low-cohesive soils in Nigeria. Conversely, Koci et al. (2021) managed to reduce gully headcut retreat from 4.3 to 1.2 m² per year in a savannah area by correctly implementing structures to redirect water flow from gullies.

When dealing with non-easily reversible linear erosive features like gullies and ravines, several control and recovery strategies can be employed. Initially, the affected area should be fenced off to prevent animal and human access, thus avoiding accidents and soil compaction (Filizola et al., 2011). Wilkinson et al. (2018) observed a 77% reduction in sediment production in areas where grazing was excluded compared to grazed gullies. Abdo et al. (2013) also noted that excluding cattle enables vegetation resurgence in affected gully and ravine areas. Firebreaks should be established to prevent fires from reaching the targeted area. Subsequently, draining the channel soil can facilitate the implementation of remaining reinforcement techniques, such as constructing sedimentation dams and revegetating the area (Shi et al., 2019). The drained water can be directed to stabilized areas or watercourses, and bamboo (*Bambusa vulgaris* sp) bundles can be used as an alternative material for drain construction (Filizola et al., 2011; Velasquez; Righes, 2019).

Check dams are widely used for gully and ravine control and recovery (Figure 4). These transversal structures are installed in the main channels of erosive processes or areas with concentrated runoff and can be constructed from various materials, including bamboo, logs, earth, cement, stone, gabion, polyethylene bags filled with soil, living vegetation, and other available materials (Chaves et al., 2012; Santana; Nunes, 2015). These barriers are constructed in order to induce channel aggradation (sedimentation), thereby decreasing gully and ravine depth and slope, as well as diminishing the speed and energy of concentrated surface runoff, promoting light sediment transport for ecosystem sustainability (Wilkinson et al., 2018). Spillways can be built over the check dams to enhance flow, reduce subsurface water flow, and soil piping occurrences (Nyssen et al., 2004). Additionally, animal burrows can lead to soil piping, creating channels in the soil that may evolve into ravines and gullies.

Figure 4. Ravines and check dams (palisades) located in plinthic soil in the municipality of São Cristóvão, Sergipe state, Brazil.

Machado et al. (2010), in their evaluation of terraces and check dams, noted minimal sediment production for recovered gullies (≦ 1.8 Mg) and none for recovering gullies. However, sediment production for active gullies was significantly higher, ranging from 20.5 to 52.5 Mg in each measurement. The study revealed that implementing terracing and check dams reduced nutrient losses by over 96% compared to active gullies without these practices. In Pindorama, São Paulo state, Abdo et al. (2013) discovered that the construction of grass-covered (*Paspalum notatum*) earth dams, coupled with concrete spillways, stabilized and rehabilitated a gully-affected area, attracting fauna and flora. Carvalho et al. (2020) and Holanda et al., (2017) examining *Paspalum millegrana Schrad*., highlighted its significant biotechnical characteristics for soil bioengineering to control erosion on slopes and riverbanks.

Gullies filled with sediments contribute significantly to lateral support for surrounding slopes, thereby reducing soil mass movement risks in associated areas. Although the initial implementation of check dams (palisades) leads to pronounced channel aggradation, this process slows over time (Bombino et al., 2022). Nyssen et al. (2004) assessed 400 sedimentation dams in Ethiopia, noting a 39% collapse rate over two years. They attributed dam failures mainly to the relationship between dam drainage area and slope, underscoring the need for multiple erosion mitigation strategies. Francisco (2016), using stake measurements, recorded lower soil loss in a gully with *Bambusa vulgaris* palisades compared to an untreated gully.

In active gullies, containing lateral slopes and headcuts may be imperative. Geotextiles are the most prevalent materials used for slope containment (Figure 5). These can be synthetic, natural, or a blend of both. Synthetic geotextiles are typically made from materials like polypropylene, which can be photodegradable or not (Wu et al., 2020). Biological geotextiles, derived from plant residues like palm leaves or straw, stabilize gullies by forming a physical barrier against erosion and promoting vegetation growth (Guerra et al., 2015). Holanda et al. (2020) investigated the resistance of geotextiles made from *Typha latifolia* Linn., while Holanda et al. (2024) explored the potential of natural fibers such as *Typha domingensis* for sustainable applications, particularly in soil bioengineering techniques, emphasizing ecological compatibility in their applications.

Figure 5. (a) Geotextile on the river slope, (b) synthetic geotextile, and (c) natural fiber geotextile in the municipality of Santana do São Francisco, Sergipe state, Brazil.

Source: The authors

Conversely, lateral slope stabilization or reshaping represents a safer technique involving the reconstruction of lateral slopes to ensure stability (≤ 45°). The objective is to halt erosion-induced channel deepening and the occurrence of mass movements. Before undertaking lateral slope stabilization, protecting the channel bottom soil with geotextile, riprap, or vegetation is necessary, along with adopting drainage strategies. Although slope stabilization projects often incur high costs, they frequently offer immediate and enduring solutions to gully and ravine evolution (Frankl et al., 2021; Singh et al., 2020).

Guerra et al. (2015), in the municipality of São Luís, Maranhão state, Brazil, analyzed that stabilization and rehabilitation of an urban gully through lateral slope stabilization, terrace construction, installation of *Mauritia Flexuosa* geotextiles, and seeding with *Urochloa decumbens* grass were effective to control erosion and resisted an intense and prolonged rainfall over 700 mm in one month

Revegetation is a strategy applicable to maintaining the stability of areas affected by gullies or ravines. When natural revegetation is unfeasible, species resilient to the area's adverse conditions must be introduced. Generally, introduced vegetation should withstand low fertility conditions, high surface flow events, and flooding (Scotton & Andreatta, 2021). The introduction of vegetation is expected to improve soil structure, water retention, organic matter content, and nutrient concentration in the gully and ravine microenvironment, facilitating natural colonization with surrounding species (Wang et al., 2021). Koci et al. (2021), in an eight-year study in a savannah area, observed significant regeneration of natural vegetation in the stabilized channels of gullies due to increased organic matter soil content and fine sediment storage provided by porous sedimentation dams.

One method to accelerate the population of plant species is by introducing fast-growing *Fabaceae* (leguminous) plants. These plants can associate with nitrogen-fixing bacteria and arbuscular mycorrhizal fungi, enhancing their nutrient absorption, particularly nitrogen and phosphorus, and water retention abilities (Ingraffia et al., 2019; Matos et al., 2023). By supplying organic matter to the soil (leaves and other plant residues) in conjunction with the sedimentation process, other species may be established more readily (Franklin et al., 2020; Mcdaniel et al., 2023).

The selection of species for erosion control must consider two key characteristics (Frankl et al., 2021): their ability to reduce erosion and capture sediments based on both the plant's aboveground and subsurface parts (root system) and their capacity to grow, survive, and reproduce in gully channels and on the banks. Grasses and shrubs with high resistance can effectively contribute to reducing erosive processes by promoting sediment accumulation. One of the most commonly used species for revegetating gully channels and sidewalls is Vetiver grass (*Chrysopogon zizanioides*), known for its extensive root system that can reach depths of up to 5 meters (Machado et al., 2018). Marques et al. (2014), in their investigation of various grasses' survival in a Cerrado gully, observed that Vetiver grass remained unaffected by the dry season, maintaining active leaf area and significant growth throughout. Prentice et al. (2023), in their research on the combined use of erosion control interventions in gullies, demonstrated that the combined application of techniques was more efficient than the isolated use of the most effective technique (check dams) being evaluated.

Conclusions

Linear erosion, comprising rills, ravines, and gullies, entails significant sediment loss, particularly in arable land, exacerbated by improper soil management, concentrated surface runoff, and extreme weather events. Its impact extends beyond the affected areas, contributing to pollution, water body siltation, and alterations in river and coastline morphology.

Techniques for controlling linear erosion fall into two categories: general soil and water conservation strategies and specific measures for areas prone to concentrated surface runoff. Practices such as contour plowing, terracing, vegetative barriers, crop rotation, and the adoption of no-till or minimum tillage methods mitigate erosive processes and helps in gully and ravine stabilization. Concurrently, interventions targeting these erosive features facilitate process stabilization and gully environment restoration, fostering local flora and fauna survival.

Effective strategies for ravines and gullies consider fencing off affected areas, constructing runoff diversion structures, installing physical barriers like palisades, slope regrading, and initiate revegetation efforts.

Combining specific strategies with soil and water conservation techniques maximizes erosion control effectiveness.

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