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Functional stability: From soil aggregates to landscape scale in a region severely affected by gully erosion in semi-arid central Mexico

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ABSTRACT

Soil aggregate stability is a vital indicator of soil structure and potential degradation and is essential to understand gully erosion in arid and semi-arid regions. Stability of soil aggregates depends on soil mass properties, local conditions (within the gully), and hillslope conditions. The objectives of this study were 1) to analyze soil aggregate stability at three gully wall positions: headscarps, sidewalls, and gully bottoms, and 2) to explore the relationships between soil aggregate stability and local and landscape conditions to know how stability at different scales is interrelated. Soil macro aggregate stability was estimated from soil samples using the soil aggregate stability kit. Conversely, Cornell infiltrometers were used to evaluate soil microaggregate stability by applying 5-min rainfall events with an intensity of 150 mm^{-1}. Local (within gully) conditions were registered in the field using indicators from the ephemeral drainage line assessment method. Landscape conditions (outside gully), such as terrain attributes, anthropogenic features, and vegetation cover, were computed from topographic maps, digital elevation models, and satellite imagery. Relationships between soil aggregate stability and local and landscape conditions were explored using classification and regression trees. The highest soil macro and micro aggregate stability were found at the gully headscarps, while gully bottoms had the lowest soil aggregate stability. Soil macroaggregate stability was related to terrain attributes, ground cover, and gully dimensions. In contrast, microaggregate stability was associated with ground cover, terrain attributes, gully dimensions, and distance to roads and farm dams. Our study showed that soil aggregate stability differs along gully walls and that soil aggregate stability can be related to different variables at the local and hillslope scales. This knowledge is a valuable indicator for understanding gully erosion and the foundation for restoration strategies in semi-arid regions.

1. Introduction

Soils in arid and semi-arid zones are exposed to high rates of soil water erosion (Borrelli et al., 2017; Ziadat and Taimeh, 2013), one of the most widespread forms of soil loss in the world (García-Ruiz et al., 2016). Soil erosion in drylands requires an integrated understanding of how high-intensity rainfall events (Cerdà, 1999), low relative vegetation cover and distribution (Muñoz-Robles et al., 2011), and anthropogenic factors such as land use change (Zhao and Hou, 2019) contribute to erosion susceptibility.

Soil erosion is a highly complex process. The interactions among the factors triggering soil erosion (e.g., rainfall intensity, ground cover, soil properties, and topography) may decrease soil aggregate stability (Bronick and Lal, 2005) which is the susceptibility of soil particles to disaggregation by eroding agents such as rainfall (Cerdà, 1998; Xiao et al., 2018). Soil aggregate stability is an essential indicator of soil functioning (Bronick and Lal, 2005; Cerdà, 2000; Fu et al., 2020; Li et al., 2021; Vermang et al., 2009). High aggregate stability decreases

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surface runoff and soil erosion and favors water infiltration, soil aeration, porosity, and productivity while reducing surface compaction (Barthès and Roose, 2002; Vaezi et al., 2018). Different sizes of soil aggregates result in differential erosional responses (Torri et al., 1998) by macroaggregates (>250 μm) and microaggregates (<250 μm; Tisdall and Oades, 1982), hence the relative proportion of macro and microaggregate of certain soil types together provide a complete characterization of aggregate stability (Amézketa et al., 2003).

In addition, the instability of soil aggregates can accelerate gully formation (Igwe and Ejiofor, 2005; Yaloon, 1987), an extreme form of soil erosion (Casabella-González et al., 2021) that strongly impacts arid and semi-arid regions; due to its severe irreversible impact on landscape function, it is considered an indicator of desertification (Lal, 2001). Gully erosion results from multiple interactions among different environmental and anthropogenic variables (e.g., increased rainfall, exceeded topographic thresholds, a decrease in vegetation cover, and construction of roads; Poesen et al., 2003) acting on a local scale with landscape scale functional impacts (Cantón et al., 2009). At the local scale, features within gullies such as existing vegetation on gully walls and floor, the shape and profile of the drainage line, the particle size of materials on the drainage line and gully wall, the shape of the ravine's contour, and the regulation of lateral flow all contribute to gully stability (Tongway and Ludwig, 2011). Moreover, gullies are critical elements of connectivity (or disconnection) at the landscape level and constitute morphological evidence of dysfunction and instability (Kakembo et al., 2009; Poesen, 2011). Stability is a concept that involves many aspects and principles from both ecological and socioeconomic perspectives; landscape stability is related to changes in biodiversity, ecosystem functions/services, and human well-being (Prokopová et al., 2019), derived mainly from land use transformation. In the case of gully erosion, the relationship between topographic factors such as drainage area and slope are also recognized as landscape instability indicators (Muñoz-Robles et al., 2010). Topographic features play a fundamental role in the initiation and expansion of gully erosion (Gómez-Gutiérrez et al., 2015) and influence the spatial variation of hydrological conditions (e.g., runoff rate, soil moisture, subsurface flow) and slope stability. Terrain curvature describes where erosion deposition can occur. Tangential curvature indicates convergence or divergence as water flows over a point (Mitas and Mitasova, 1998), while profile curvature is defined as the surface curvature in the direction of the steepest slope (in the vertical flow line), which modifies the velocity of the flow that drains the surface and the deposition of sediments (Rahmati et al., 2022). Other useful indices describe surface runoff processes in more detail: the topographic wetness index indicates zones of saturation or variable sources for runoff generation considering catchment area and slope (Moore et al., 1991), and the stream power index indicates the topographic control of hydrological processes related to the erosive power of runoff (Rahmati et al., 2017). Ground cover and its distribution may also affect landscape instability, as its reduction increases surface runoff and reduces resistance to concentrated flow erosion (Chen et al., 2018). Anthropogenic features such as land use change, road infrastructure, and inappropriate soil management accelerate gully development by concentrated surface runoff and affect landscape stability (Igwe, 2012; Valentin et al., 2005; Zádorová et al., 2011).

The observation scale is related to the mechanism of soil erosion, resulting in erosion patterns that change at different scales (Huang et al., 2017). Thus, a multi spatio-temporal assessment of soil erosion dynamics provides insights into controlling factors and how different land uses affect soil stability at various levels (Gambella et al., 2021; Veldkamp et al., 2001). In the context of gully erosion, studies of soil aggregate stability are still scarce (Igwe and Ejiofor, 2005; Oluyori and Mgbanyi, 2014), and only a few provide integrated assessments of soil erosion dynamics and its drivers at local and sub-catchment scales (Sonneveld et al., 2005). From a hydrological point of view, it is important to analyze runoff and vertical flow occurring at the gully walls that can influence soil aggregate stability. For instance, runoff reaches the gully at headscarps, where, if soil detachment occurs, it is mainly related to hillslope conditions (e.g., slope gradient, low surface cover). Once runoff enters the gully, cracks in the walls result in a transient flow of water towards the middle of the gully (Collison, 2001). Finally, horizontal water flow within the gully can result in undermining and tunnel erosion at the gully bottoms; both are related to how water enters the gullies, either by surface flow or infiltration (Day et al., 2018). However, these factors are rarely integrated into gully erosion studies dealing with soil aggregate stability or related to variables at different scales. Therefore, a significant challenge to be addressed is the multi-scale integration of processes, analyses, monitoring, and management practices into models to assess gully erosion (Sidle et al., 2019) to support the implementation of soil erosion control measures with more effective results (Bird et al., 2007).

In this study, we analyzed soil stability by integrating soil aggregates (individual soil aggregates), local scale (within gullies), and landscape scale (hillslope condition) in an area affected by a complex interconnected deep gully system in a mountainous area formerly covered by an oak forest ecosystem in the Central Plateau of Mexico. This region has historically been impacted by mining, deforestation, cattle grazing, and expansion of road infrastructure (Martínez-Chaves et al., 2010). The objectives of the study were to: 1) determine the stability of soil macro and micro aggregates in the gully headscarps, sidewalls, and bottom of gully walls; and 2) explore the relationships between soil aggregate stability and local (gully dimensions and activity) and landscape scale (terrain features, ground cover, roads, farm dams) variables to determine how they interact with soil aggregate stability. We expected that local and landscape scale variables would reflect the degree of soil aggregate stability of gully walls, which may be used to define priority restoration sites and strategies.

2. Materials and methods

2.1. Study area

The study was conducted in ten gullied sub-catchments between 22° 11′ and 22° 16′ N and 100° 44′ and 100° 45′ W. The sub-catchments cover 30.29 km^2 in the communities of Monte Caldera and Jesus Maria in the west part of the municipality of Cerro de San Pedro, San Luis Potosí, Mexico (Fig. 1). Cerro de San Pedro has been an important mining area dating back to 1592 (Martínez-Chaves et al., 2010). It is located within the Sierra Madre Oriental physiographic province, particularly in the Sierras y Llanuras Occidentales subprovince (Cervantes-Zamora et al., 1990), with elevations between 1,800 and 2,500 masl. Landforms include open slopes, deeply incised streams, valleys, and high ridges, with slopes ranging from 3 % to 45 %.

The study area is situated within El Salado hydrological region 37, one of Mexico's most important continental basins, which is endorheic and has intermittent streams (SINA-CONAGUA, 2020). The climate is semi-arid (BS_1kw), with a mean annual temperature ranging between 10.5 °C and 26 °C and a mean annual rainfall of 325 mm (García, 1973). Torrential storms of high intensity (up to 150 mm h^{-1}) and short durations have been recorded at the nearest weather station and can trigger high runoff and soil erosion. The surface lithology consists of Cretaceous limestone rocks that include slope deposits of a carbonate paleoplatform (SGM 2017). The lutite–sandstone formations represent the final stage of sub-catchment fill. Other lithological formations are the Indidura, Santa Maria ignimbrites, and the Casita Blanca Andesite. The predominant soil types are textured clay loam (INEGI, 1973), shallow leptosols (<30 cm) on rocky slopes, with kastanozem associations in the northern portion of the study area, while associations with rendzines and luvic feozems predominate in the south. The main vegetation types are oak forest, secondary grasslands, and chaparral (Calderon, 1960).

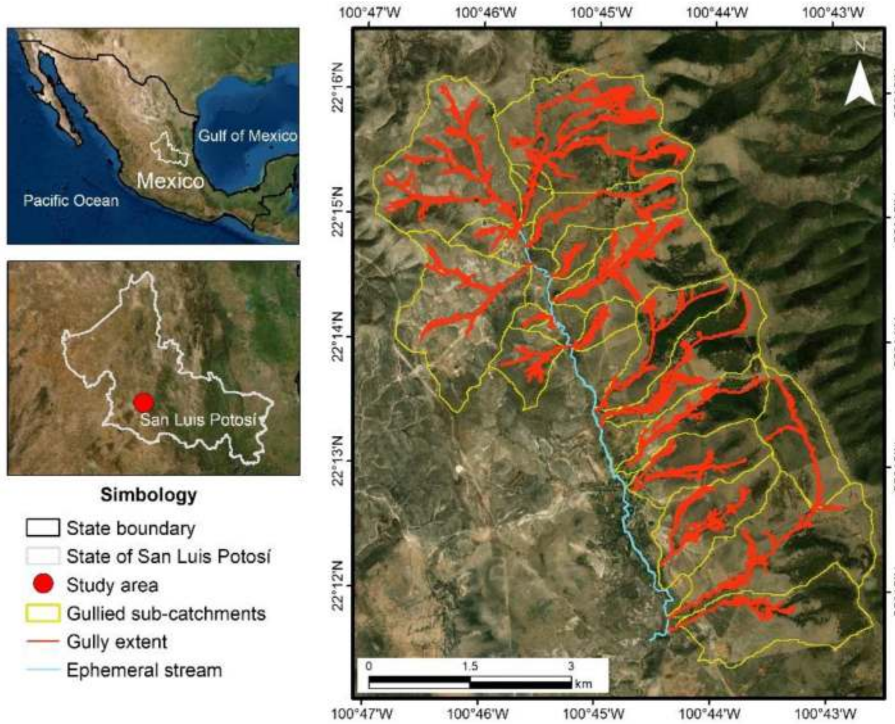

Fig. 1. Location of gully sub-catchments in Cerro de San Pedro, SLP, Mexico.

2.1.1. *Land use history and gully development*

Gully formation and erosion in the study area have been related to gradual but continual changes in land use over the past 430 years. Consequences of an emerging regional mining industry since 1592 include massive ecosystem transformation at the landscape scale, resulting in fragmented mosaics of natural and secondary forests, grasslands, and open dryland vegetation (Martínez-Chaves et al., 2010). Several periods of vigorous economic development (between 1904 and 1948) introduced human settlements and agricultural activities related to providing food, water, metals, charcoal, and firewood, which caused extensive deforestation (Palacios-García, 2008). Periods of economic instability in the mining sector (1948–1997) induced current land use practices that include extensive caprine and bovine grazing as well as corn and bean cultivation in small plots for self-supply (Martínez-Chaves et al., 2010). These continual landscape transformations have increased surface runoff and soil erosion, contributing substantially to the beginning and expansion of the gully system in the study area.

2.2. *Sampling sites*

The ten gullied sub-catchments were selected for field measurement and derived from a LIDAR digital elevation model with a spatial resolution of 5 m in ArcMap 10.3 (ESRI, 2013). Gully boundaries were manually digitized on a 2019 Ikonos image with 0.50 m spatial resolution, freely available through Google Earth Pro.. For each gully, the length of the main drainage line was measured (Table 1), and eleven equidistant points were selected along the main drainage line, distributed from the beginning to the terminus of the respective gully, for field data collection. Gully depth and width were measured at each field sampling point at the gully base and the gully bank (Table 1; Fig. 2). Additionally, gully boundaries were validated at each sampling point and verified with a differential GPS where tree canopy cover had obstructed visibility for manual digitalization on the Ikonos image.

Three soil samples were taken with a spatula at each sampling point along the gully walls for further aggregate stability assessment. Soil samples were collected at the headscarps (surface soil 0 to 10 cm), gully bottoms (up to 30 cm above gully floor), and sidewalls (the midpoint between the headscarp and gully floor). Aggregate stability from headscarps correspond to the point where runoff reaches the gully; sidewalls represent the point where water infiltrates through cracks in the gully banks, and the bottom position of the gully relates to the water flowing in the gully channel, which may cause tunnelling and undermining. Therefore, samples from these three gully wall positions can reflect soil aggregate stability characteristics from a hydrological

Table 1
Main characteristics of measured gullies (total for gully length; average, minimum, maximum for all other variables) and dominant vegetation (around the gullies), type within gully sub-catchments. n = 110 sampling points within gullies.

Sampled gully	Total drainage line length (m)	Width at gully bank (m)	Width at gully base (m)	Gully depth (m)	Vegetation cover (%)	Vegetation type
1	1,806.9	32.5 (5.2–131.5)	4.0 (1.5–17.9)	4.4 (0.4–38.0)	69.0 (35.4–92.1)	Grassland
2	5,485.0	17.9 (4.8–64.7)	4.6 (1.5–9.8)	8.0 (1.3–34.5)	86.1 (49.4–99.0)	Grassland/forest
3	1,914.4	26.9 (2.0–99.5)	2.2 (1.0–4.1)	8.6 (0.3–36.1)	68.5 (24.5–97.6)	Grassland
4	2,857.6	13.3 (1.1–51.8)	4.8 (2.1–11.3)	4.6 (1.2–14.4)	75.9 (44.3–97.3)	Grassland
5	3,601.8	28.0 (3.4–81.3)	5.7 (2.5–7.7)	13.5 (1.1–36.2)	81.5 (57.4–97.0)	Grassland/forest
6	3,070.4	11.8 (4.0–50.3)	2.8 (1.2–4.0)	4.2 (0.8–9.6)	81.9 (58.5–96.5)	Grassland/forest
7	842.2	47.5 (13.3–90.0)	6.0 (2.5–16.0)	12.8 (3.4–27.0)	63.0 (19.8–85.9)	Grassland
8	2,805.3	40.8 (5.1–75.5)	8.0 (3.0–30.0)	8.7 (0.7–16.6)	66.9 (21.9–95.5)	Grassland
9	800.2	10.4 (3.9–21.4)	1.9 (1.3–3.7)	6.3 (1.6–6.4)	65.7 (34.8–90.0)	Grassland
10	2,722.8	16.6 (3.2–30.6)	4.5 (2.0–10.8)	5.6 (1.2–14.6)	69.2 (26.7–95.7)	Grassland

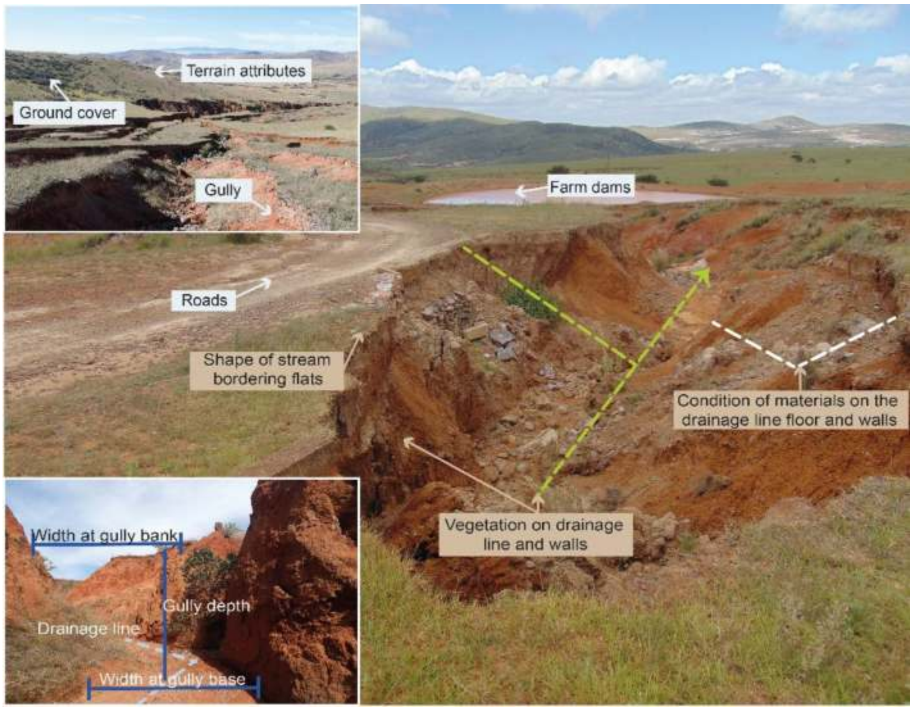

Fig. 2. Gully erosion features in the study area showing the main characteristics at local and landscape scales.

perspective.

2.3. Assessment of soil aggregate stability

Aggregate stability of macroaggregates and microaggregates was assessed for the headscarps, sidewalls, and gully bottoms. Before running the soil aggregate stability tests, samples were air-dried for 48 h.

2.3.1. Stability of macroaggregates

The field stability kit provides information on soil structure and erosion resistance based on biotic integrity (organic matter) that holds the soil aggregates together (Herrick et al., 2001). A visual evaluation of the fragmentation process of individual 6 to 8 mm diameter soil aggregates once immersed in distilled water was made and scored with aggregate stability values from 1 to 6. Scoring is based on the time it takes for soil aggregates to break down (i. e., percentage of lost structural stability), which can comprise from 5 s to 5 min; criteria for assigning scores are found in (Herrick et al., 2001). A score of 1 indicates collapsed or very unstable aggregates, 2 means unstable aggregates, 3 and 4 potentially stable aggregates, 5 stable aggregates, and 6 indicates intact or very stable aggregates.

2.3.2. Stability of microaggregates

A Cornell infiltrometer was used to evaluate how soil aggregates resist disintegration when impacted and wetted by raindrops (Moebius et al., 2007). This rainfall simulator works by gravity through the formation of drops that pass through several spiral capillary drip tubes at the bottom, which are controlled by a bubble tube that also serves to regulate the intensity of rainfall by modifying its height (Ogden et al., 1997). Soil samples from each gully wall position were sieved to obtain soil aggregate sizes from 0.25 mm to 2.00 mm. A 30 g soil subsample was spread in a single layer over the surface of a 0.25 mm sieve and placed 0.5 m underneath the Cornell infiltrometer. The rainfall simulator was filled with distilled water, and rainfall was applied at 150 mm h^{-1} for 5 min. This rainfall intensity and duration resembles natural storms with a 10-year return interval in the study area. After each rainfall simulation, the unstable aggregates and the water passed through the sieve were oven-dried at 105 °C for 24 h. The remaining soil left on the sieve (i.e., stable aggregates) was also oven-dried. Dry samples were weighed, including the organic material (i.e., plant parts) and rock fragments. Finally, the percentage of soil mass was determined after subtracting the weight of organic material and rock fragments from the sample.

2.4. Characterization of local and hillslope conditions

Soil aggregate stability may be related to local scale traits within the gully channel, but also associated with landscape scale processes controlled by soil, topography, and vegetation management (Morgan, 2005; Zádorová et al., 2011). Data describing within-gully and hillslope attributes (Fig. 2) were used to analyze the relationship of soil aggregate stability with local and landscape conditions (Tables 3 and 4). Descriptive statistics of these variables are shown in Table 1 of the Supplementary material.

Along with gully dimensions (Table 2), gully stability was analyzed at the local scale using the ephemeral drainage line assessment or DLA (Tongway and Ludwig, 2011). The method consists of eight visual indicators (Table 3) used to classify the state of gully stability as very active (<50 %), active (50–59 %), potentially stable (60–69 %), stable (70–80 %) or very stable (80–100 %). The indicators were scored at each of the 11 sampling points of the ten gullies evaluated in the field.

Attributes of the hillslopes (Table 4) were determined by topographic indices derived from the 5-m LIDAR digital elevation model and were computed with Whitebox Geospatial Analysis Tools 3.4.0.

Vegetation cover is one of the main ecohydrological determinants of infiltration, runoff, soil properties, and susceptibility to soil erosion in semi-arid environments (Muñoz-Robles et al., 2011). The proportion of vegetation cover was mapped using a Sentinel 2A multispectral satellite image with a spatial resolution of 10 m, obtained from the European Space Agency . After radiometric and geometric correction, the normalized difference vegetation index (NDVI) was estimated (Table 3). The NDVI describes vegetation greenness and vigor based on the difference between visible and near-infrared reflectance of vegetation cover (Chuvieco, 2010). The NDVI was calibrated by measuring ground cover in 10 × 10-m geo-referenced field plots (n = 79). A polynomial

Table 3
Indicators of the drainage line assessment (DLA) method to evaluate gully stability at the local scale (Tongway and Ludwig, 2011).

Indicator group	Indicator	Description
Indicates low energy flow as vegetation cover increases	Vegetation on drainage line floor	Evaluates the erosion resistance of the drainage line by vegetation cover. Includes recording vegetation cover growing on gully floor.
	Vegetation on drainage line walls	Measures the resistance to erosion on the gully wall. Includes recording vegetation cover growing on gully wall.
Indicates the energy available to erode or deposit different materials	Shape and aspect ratio of drainage line cross-section	Defines areas based on the magnitude of the degree of erosion on their vertical or rectangular cross-sectional shape. It considers evidence of tunneling, undercutting, and gully wall angle.
	Longitudinal morphology of drainage line	Assesses the predominant flow of the drainage line and its interaction with the characteristics of the adjacent hillsides. It considers whether incising bed in pre-existing loose sediment is in place or evidence of recent sediment movement.
	Particle size of materials on drainage line floor–material available for erosion	Type of material that is potentially moved during soil erosion. It considers the material size on the gully floor compared to the size on the gully wall.
Indicates slaking or dispersing susceptibility	Nature of drainage line wall materials	Assesses the instability of soil aggregates in the gully wall. It considers exposed materials that slake or disperse.
Indicates whether high water flows result from lateral flow from the catchment	Shape of stream-bordering flats and slopes	Assesses whether the high-water flow is coming upstream or from a lateral source. It considers the slope of gully bank.
	Nature of lateral flow regulation into the drainage line	Determines the source of lateral flow around the drainage line. It considers vegetation cover at the bank edges.

regression model was built to estimate ground cover from the NDVI; the model was significant ($P < 0.05$) with an r^2 of 0.92.

Anthropogenic linear landscape features such as roads concentrate and increase the drainage area, stimulating the development of large gullies (Nyssen et al., 2002). Farm dams and road networks were digitized in Google Earth Pro , and their Euclidean distance to each sampling point within gullies was computed.

The drainage area for each sampling point was determined, and their polygons were used to extract the average values of the topographic indices and vegetation cover using zonal statistics in ArcMap 10.3 (ESRI, 2013).

2.5. *Data analysis*

Based on the nature of the ordinal qualitative variables of the field stability kit method and non-normal data, macroaggregate stability means were analyzed with the Kruskal-Wallis test. A one-way analysis of variance (ANOVA) was used to analyze the percentage of stable soil microaggregates from rainfall simulations; assumptions of normality of residuals and homogeneous variance were met. Pairwise contrasts were used to identify differences in soil aggregate stability between head-scarps, sidewalls, and gully bottoms for macroaggregates and micro-aggregates. Significance levels were set to $P < 0.05$. The classification and regression trees algorithm (CART) was used to identify the most important variables at the local and landscape scales (Tables 3 and 4) to explain soil macro and micro aggregate stability. This CART is a non-parametric method which consists of a recursive binary partition procedure with the ability to process explanatory and nominal continuous variables in homogeneous subgroups that use algorithms to minimize the variance (Breiman et al., 1984; Gómez-Gutiérrez et al., 2009). For macroaggregate stability, classification trees were constructed for each gully wall position, using the stability classes obtained from the field stability kit method as the response variable. For the stability of microaggregates, regression trees were created using the percentage stability from the rainfall simulations for each gully wall position as the continuous response variable. Relative importance variable values from CART trees are reported, while classification and regression trees can be found in Supplementary Materials (Fig. 2a–2f). All the statistical analyses were run in RStudio version 3.6.3, and CART trees were built using the *rpart* library.

Table 4
Description of variables used to characterize hillslope conditions (landscape scale).

Variable group/name	Description/Reference
Terrain attributes (all derived from a 5-m LiDAR DEM)	
Number of upstream neighborhood pixels	Associated with planimetric area of the flow accumulation area at each sampling point.
SPI (Stream power index)	Measures erosive power of water flow (dimensionless) (Moore et al., 1991)
TWI (Topographic wetness index).	Quantifies topographic control in hydrological processes (dimensionless) (Lucà et al., 2011).
Slope	% slope of the upslope area draining to each sampling point.
Profile curvature	Direction of maximum slope; determines the acceleration or deceleration of surface runoff 1/m (Shary et al., 2002).
Plane curvature	Convergence or divergence of slopes (A-concave, B-convex or C-flat, 1/m) (Shary et al., 2002).
Tangential curvature	Topographic curvature measured in the direction of tangent to contour at a given point (dimensionless; (Luo and Stepinski, 2006).
Distance to sub-catchment outlet	Flow distance between sampling points along the sub-catchment boundary (m).
Vegetation cover	
Ground cover	Proportion of surface soil covered by vegetation (%). Cover map derived from the normalized difference vegetation index (NDVI).
Anthropogenic features	
Distance to roads and farm dams	Euclidean distance from each field sampling point to roads and farm dams (m).

Table 2
Description of variables used to characterize gully dimensions (local scale).

Variable group/name	Description/Reference
Width at gully bank	Distance between gully walls at the top of the wall (m)
Width at gully base	Distance between gully walls at the drainage line (m).
Depth	Distance between the top edge and the drainage line at the bottom of the gully (m).
Volume	Estimated average soil loss volume was obtained by multiplying the area by length of each gully section (m^3).

3. Results

3.1. Soil aggregate stability

Soil macroaggregate stability as determined with the field stability kit was highest in the headscarps, followed in decreasing order by sidewalls and gully bottoms ($P < 0.05$; Fig. 3a).

Soil microaggregate stability as measured using rainfall simulations was higher at the headscarps and sidewalls than at the gully bottoms ($P < 0.05$; Fig. 3b), but did not differ between headscarps and sidewalls ($P > 0.05$).

3.2. Gully stability

Gully stability evaluated with the eight visual indicators from the DLA showed that overall, all gullies were active (DLA score = 50.6 %). The nature of lateral flow regulation into the drainage line and vegetation on the drainage line walls were the most important criteria contributing to gully stability (Fig. 4), followed in decreasing order by shape and aspect ratio of drainage line cross-section, longitudinal morphology of the drainage line, and particle size of materials on drainage line floor, which contributed equally to gully stability.

3.3. Variables at local and landscape scales related to macroaggregate and microaggregate stability

For macroaggregates, the relative importance of landscape scale variables contributing at least 50 % to soil stability varied by gully wall position (Fig. 5). Terrain variables and vegetation cover contributed the most to improving the classification trees for the headscarps (Fig. 5a). Mean distance to farm dams, gully depth, and terrain attributes had the highest relative importance explaining macroaggregate stability for the sidewalls (Fig. 5b). Gully depth and terrain attributes were the variables most closely associated with macroaggregate stability at gully bottoms (Fig. 5c).

For microaggregates, the relative importance of explanatory variables contributing at least 50 % to soil stability also varied by position on the gully wall. Minimum ground cover, terrain variables, width at gully bank, and the mean distance to farm dams contributed the most to improving the classification trees for the headscarps (Fig. 5d). Terrain variables, distance to sub-catchment outlet, and ground cover had the highest relative importance for microaggregate stability of the sidewalls (Fig. 5e). Distance to farm dams, distance to roads, minimum ground cover, terrain variables, gully depth, width at the gully base, and width at the gully bank all explained microaggregate stability at the gully bottoms (Fig. 5f).

4. Discussion

4.1. Soil aggregate stability at gully walls

Different levels of aggregate stability across gully walls result from the complex and dynamic process involved in soil aggregation; that is, from the formation, stabilization, and disintegration of soil particles (Barthès and Roose, 2002; Lehmann et al., 2017). Knowledge about soil aggregate stability in gullies is essential for explaining their development, and in some instances, it has been used to determine the mechanism of gully formation (van Zijl et al., 2013). Soil aggregate stability is considered the most appropriate indicator to describe slope protection from erosion and shallow mass movements, as it is critical both to enhancing plant growth and to reducing soil erodibility (Barthès and Roose, 2002; Cantón et al., 2009; Xiao et al., 2017). However, studies of soil aggregate stability in gullied semi-arid regions are still scarce (Nciizah and Wakindiki, 2014). Our approach to studying soil macroaggregate and microaggregate stability within gullies and their relationship with landscape features enables a better understanding of the gully erosion process, which may support management practices oriented to improving site productivity and landscape condition in fragile drylands (Sidle et al., 2019).

Assessing the stability of coarse and fine aggregates is essential for effective control of soil loss at local and landscape scales in semi-arid areas (Barthès and Roose, 2002; Vaezi et al., 2018; Zeng et al., 2018). Our results indicate higher macroaggregate and microaggregate stability at headscarps, which could be related to greater soil resistance to erosion by concentrated flow, given different surface conditions (Knapen et al., 2007) and may result in lower erosion rates compared to gully bottoms. This higher stability at the headscarps than at the gully bottoms was also observed by Oluyori and Mgbanyi (2014) and Dlapa et al. (2012). In our study area, the high soil aggregate stability at the headscarps can be explained by grass and tree cover at the gully edges, as shown by the nature of lateral flow regulation into the drainage line (from DLA). This suggests that the amount of vegetation cover at the lips of the gully bank is sufficient to decrease surface flow reaching the gully edge and limit the impact of rainfall, increasing soil macroaggregate

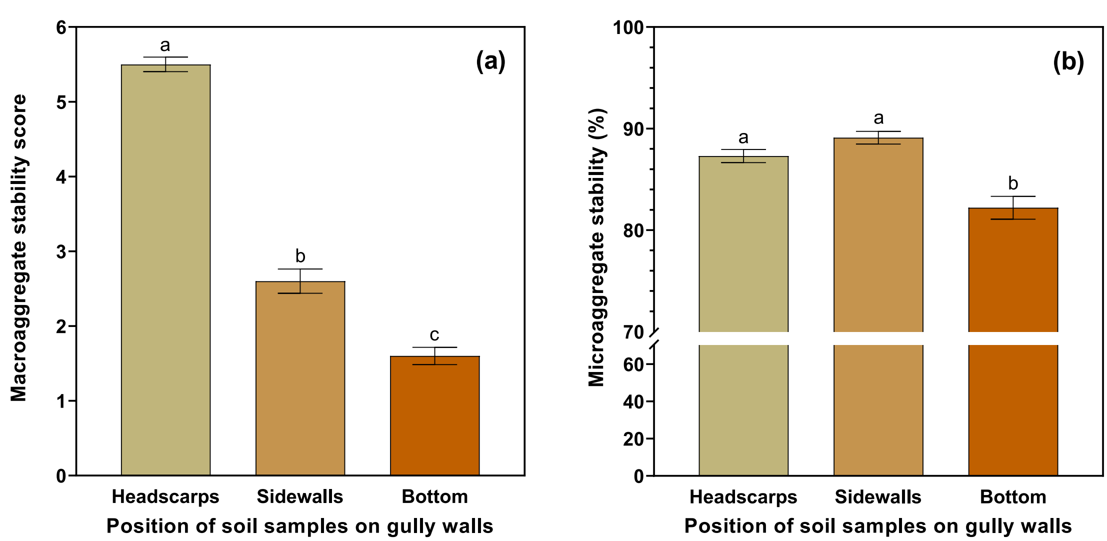

Fig. 3. Average values (±SE) of (a) soil macroaggregate stability (1 = very unstable, 6 = very stable) from the field stability kit at three gully wall positions, and (b) percentage of soil microaggregate stability from rainfall simulation tests. The column averages followed by different letters are significantly different ($P < 0.05$). n = 110 (10 gullies and 11 gully sample points within a gully) soil samples for each gully wall position.

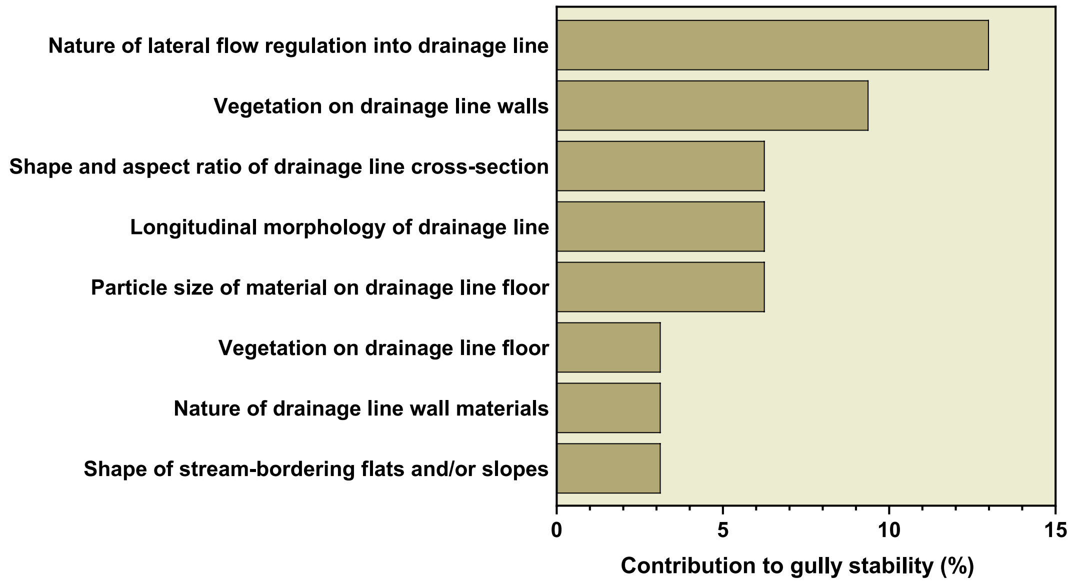

Fig. 4. Gully stability determined by the average percentage contribution of the drainage line assessment indicators. Indicators were measured at sampling points inside 10 gullies in the study area. n = 110 (10 gullies and 11 gully sample points within a gully) soil samples for each gully wall position.

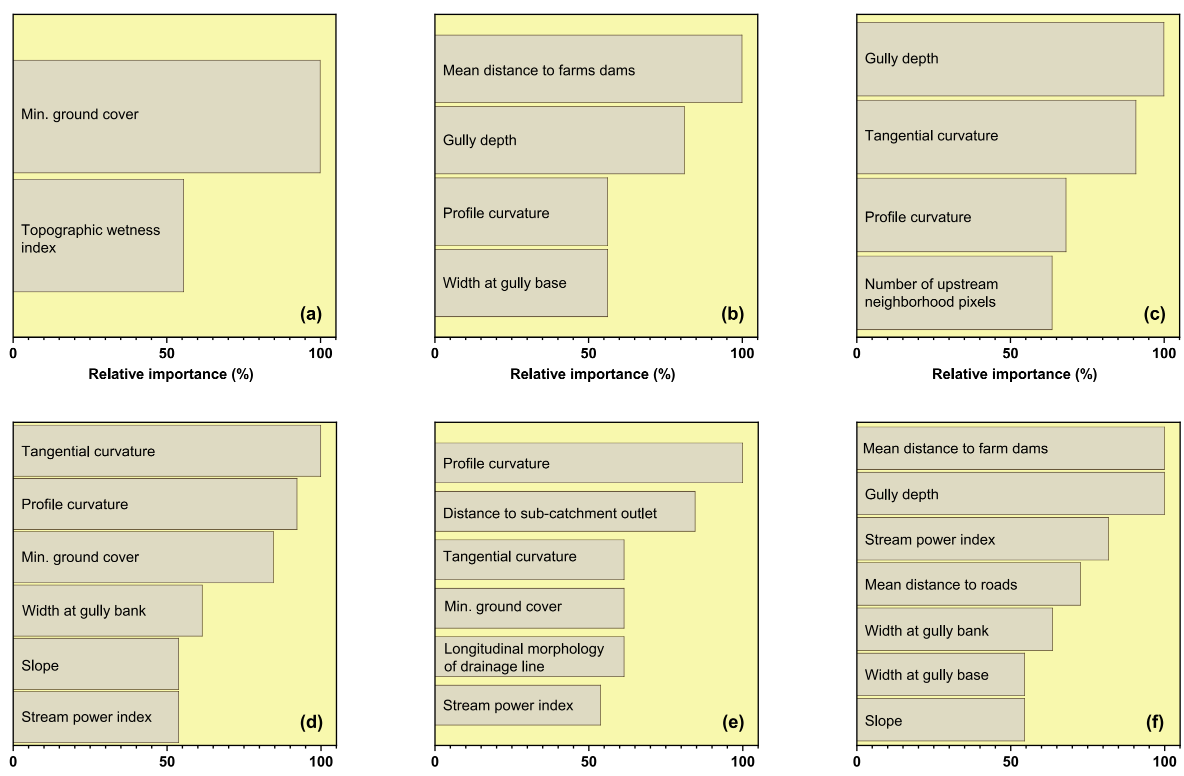

Fig. 5. Explanatory variables contributing > 50 % of the relative importance in soil macroaggregate stability from classification trees: a) headscarps, b) sidewalls, c) gully bottoms; and soil microaggregate stability from regression trees: d) headscarps, e) sidewalls, f) gully bottoms.

stability, as also found by Bird et al. (2007) and Herrick et al. (2001).

Martínez-Casasnovas et al. (2009) outlined the importance of vegetation on the structural stability of gully walls. However, it has received less attention in assessment and control of sidewall erosion, probably because gully walls can have harsh and nutrient-poor conditions, where the hydrology and soil chemical conditions may inhibit vegetation establishment and growth (Shellberg and Brooks, 2013). Nevertheless, vegetation can be established at headscarps and gully bottoms for restoration since the plants provide dense root networks that retain soil and accelerate soil-forming processes, which can reverse the low aggregate stability of gully walls as found in other permanent gully systems (Dlapa et al., 2012).

Regarding gully sidewall processes and stability, the increased lateral flow may reach a less permeable zone during high-intensity storms, decreasing soil resistance and increasing cracking over the gully wall (Collison, 2001; Igwe and Ejiofor, 2005). This effect may cause partial or complete collapse of the soil and trigger mass erosion of sidewalls, yielding, in some cases, more sediment than the initial linear incision (Blong et al., 1982; Luffman et al., 2015) and wider gullies. In our sites, vegetation at the gully edges explains macro and microaggregate stability at the headscarps. However, other studies have demonstrated that persistent aromatic humic material provides high aggregate stability by agglutinating soil microaggregates (Nciizah and Wakindiki, 2014). Previous research has considered microaggregates as indicators of soil erosion because when they disaggregate, they obstruct the soil pores, reduce water infiltration and increase runoff (Igwe and Obalum, 2013). Our results showed that sidewall microaggregates were as stable as those at the headscarps. However, as vegetation cover is scarce on the gully walls, microaggregate stability may be more related to other factors including the cohesiveness of the sediment and the presence of a more resistant capping layer (Kirkby and Bracken, 2009) or to the properties that hold these smaller particles together (Knapen et al., 2007). Finally, the inherent stability of materials (Collison, 2001) may be critical, as microaggregates may have higher recalcitrant C components and provide a long-term stabilizing effect (Peng et al., 2017).

The lowest stability of soil macroaggregates and microaggregates at the gully bottoms can be related to water transport capacity at the sides of the drainage line. Flow can stimulate variations in the physical and biochemical properties of the soil that control the mineralization of organic carbon and weaken the structural stability of aggregates (Mohseni and Hosseinzadeh, 2021). High flow triggers undermining and tunneling, a feature observed in the study site, especially at locations with curves in the drainage line; the strong flow decreases soil resistance to erosion and increases gully depth (Martínez-Casasnovas et al., 2004; Rienks et al., 2000).

4.2. Linkages between soil aggregate stability and hillslope characteristics

In our study, hillslope and local scale variables were associated with soil macroaggregate and microaggregate stability at the headscarps, sidewalls, and gully bottoms. However, hillslope features appeared to be more related to macro and microaggregate stability at the three gully wall positions than local scale variables. Hillslope conditions surrounding the gully subcatchments are related to gully and landscape stability (Conoscenti et al., 2018), and there is some evidence to show their influence, especially topography, on soil aggregate stability (Cantón et al., 2009). There is little information about landscape variables contributing to soil aggregate stability in the gully wall (Oluyori and Mgbanyi, 2014). Nevertheless, some studies in semi-arid regions relate surface soil aggregate stability to several factors, especially differences in heterogeneous source distribution in semi-arid areas, particularly landscape scale terrain slope (Bird et al., 2007). In these patchy landscapes, the spatial organization of vegetation and slope gradient strongly influences the partition of rainfall into runoff and infiltration and regulates soil re-distribution (Ludwig et al., 2005). As vegetated patches retain resources such as sediments, seeds, and organic matter, and retain them along root systems, they can be expected to have high aggregate stability.

4.2.1. Terrain attributes

Terrain features are the variables most frequently related to soil aggregate stability in the studied gullies, as they influence surface runoff generation and soil erosion, which are closely related to soil aggregate breakdown (Le Bissonnais et al., 2002; Zuo et al., 2019). As topography controls flow concentration and acceleration once flow reaches unstable points in the landscape, either human-caused or natural, it can cause gully initiation and development (Gómez-Gutiérrez et al., 2015). In our sites, where tangential curvature implied convergent hillslopes, the surface flow likely increased, resulting in unstable aggregates, especially at gully bottoms. When tangential curvature was convex, microaggregates were very stable at the headscarps and gully sidewalls.

In our sites, where profile curvature was convex, the lowest aggregate stability was found, especially for macroaggregates at sidewalls and gully bottoms and for microaggregates at headscarps and sidewalls, as convexity increases flow velocity and the potential to transport sediment (Yilmaz et al., 2011).

Some studies have shown that areas with gentle slopes, such as those in our study, with high topographic wetness index and near runoff areas, tend to have a higher susceptibility to soil erosion (Rahmati et al., 2017). However, we found low topographic wetness index values in the studied gullies; they were associated with stable and very stable macroaggregates at headscarps. On the other hand, a study by Cantón et al. (2009) found that the topographic wetness index was not very affected by soil macroaggregate stability or aggregate size distribution. As the topographic wetness index was only related to soil macroaggregate stability at the headscarps in our sites, this index does not seem to be a useful landscape indicator of local-scale soil aggregate stability for other gully wall positions.

In addition, high values of the stream power index have been associated with the presence of gullies (Conforti et al., 2011; Dube et al., 2014). However, our results indicate that high index values were not necessarily related to low soil microaggregate stability. This may be due to vegetation on the hillslope, moderate slope gradient, and surface roughness that can sufficiently reduce flow velocity to disaggregate soil particles.

The potential influence of slope on soil aggregate stability in the study area can have two strands. Firstly, slope influences runoff by modifying its velocity and opportunities to infiltrate into the landscape (Rahmati et al., 2022). Secondly, limiting or increasing suitability for specific land uses requiring flat or gentle slopes enhances soil compaction and road construction (Rahmati et al., 2022) and results in concentrated runoff from larger surfaces influencing the development of gullies (Muñoz-Robles et al., 2011). Our study area is characterized by hilly areas at the top of the gullied sub-catchments and gentle slopes in the lower portions of the sub-catchments. These gently sloping areas have high anthropogenic pressure due to easy access and higher surface flow accumulation with a high potential for gully initiation. Other studies have shown that gentle to moderate slopes (0–30 %) such as the plains in our study area generally result in sites with higher exposure to gully erosion (Lucà et al., 2011).

Another important terrain variable was the number of upstream neighborhood pixels related to the drainage area upslope from each sampling point within gullies. Larger drainage areas are associated with low macroaggregate stability at the gully bottoms. The potential surface flow volume increases as the drainage area increases, making more energy capable of breaking down soil aggregates. Distance to the subcatchment outlet was also associated with microaggregate stability at sidewalls; it is an indicator of how energy is dissipated across the landscape (i.e., the power necessary to transport sediments; [Sklar et al., 2016]). However, this energy would also depend on slope gradient and surface roughness. We found no examples describing the relationships between soil aggregate stability, drainage area, and distance to subcatchment outlets from other studies to place our results in context. Thus, more research would be needed to clarify the effect of these two variables on soil aggregate stability.

Studies on the effects of topography on soil aggregate stability dynamics are scarce (Rhoton et al., 2006; Tang et al., 2010). Most studies on soil aggregate stability and terrain properties have been conducted in agricultural areas. In this land use, it has been demonstrated that terrain attributes such as slope, terrain curvature, topographic wetness index, and stream power index are closely associated with landscape spatial heterogeneity and aggregate stability (Rhoton and Duiker, 2008; Zádorová et al., 2011). Although we found that terrain attributes are related to soil aggregate stability, more research is needed to clarify how they might increase or decrease stability in gullied areas. Other terrain features may be related to soil aggregate stability; for instance, it has been shown that landscape position with respect to the topography has significant effects on soil aggregate stability (Geng et al., 2017; Wang et al., 2021) and could be included as an explanatory variable.

4.2.2. Ground cover

Ground cover plays a fundamental role in regulating runoff and infiltration (Dunne et al., 1991; Wei et al., 2007), and it is one of the critical factors influencing soil erosion (Cerdà, 1998). In our sites, ground cover had at least 60 % relative importance for macro and microaggregates at the headscarps and microaggregates at sidewalls. Research on the effects of vegetation cover on soil aggregate stability has found that vegetation can significantly increase macroaggregate stability (Tang et al., 2010), which can be attributable to the root mass density (Guo et al., 2020). Plant roots contribute to developing a stable soil aggregate structure by enmeshing soil particles and releasing glue-like root exudates (Tisdall and Oades, 1982). In our sites, having at least 0.68 % ground cover on the hillslope led to very stable macroaggregates at gully headscarps. In comparison, at least 6.0 % ground cover resulted in>91.0 % microaggregate stability at gully sidewalls and headscarps. At the hillslope scale, the primary role of ground cover in decreasing soil loss by up to 90 % has been shown, when cover is 60–70 % (Jiang et al., 1992), as runoff also varied with this threshold, which significantly decreases sediment yield (Liu et al., 2018).

4.2.3. Anthropogenic features

Distance to farm dams was associated with unstable macroaggregates at sidewalls and microaggregates at the gully bottoms; the longer the distance, the more stable the aggregates. Higher soil susceptibility to erosion has been related to distances < 50 m from farm dams (Rahmati et al., 2017). Short distances from the gullies to roads was another critical aspect for microaggregates at gully bottoms, which showed lower aggregate stability at shorter distances. In general, distances to roads between 0 and 100 m indicate a higher probability of erosion given the bare soil present, implying lower aggregate stability (Rahmati et al., 2017). At the landscape scale, construction of roads has contributed significantly to gully development (Igwe, 2012; Rahmati et al., 2022) and may decrease soil aggregate stability.

4.3. Linkages between soil aggregate stability and local scale gully conditions

Gully dimensions are related to soil aggregate stability. The differential soil aggregate stability along gully walls may influence the growth dynamics, stabilization, and morphometry within gullies (i.e., increase in width and depth or decrease of gully wall slope angle), which is an essential factor in gully formation (Dlapa et al., 2012). In general, wider gullies had high aggregate stability, suggesting that gullies would stabilize (i.e., less vulnerable to further erosion) and become less active in these sections. Conversely, low aggregate stability was associated with deep gullies. Knowing soil aggregate stability across the gully wall may give an idea of potential gully growth. However, there are other hillslope and local conditions that may be interacting to determine gully growth dynamics. The longitudinal morphology of the drainage line, a DLA indicator of gully activity, was related to stable aggregates where low energy flow was expected due to the lack of incised channel sections, which may lead to gully stabilization.

4.4. Implications for gully assessment and control in semi-arid systems

We found that soil aggregate stability is related to different variables depending on the scale of the study (i.e., local or landscape scales). Still, this relationship has rarely been explored in gullied semi-arid areas. Therefore, further research on soil aggregate stability and the variables interacting at different scales is essential to understanding the tight interrelationship between soil, gully, and landscape stability. Other work has also outlined the relevance of knowing and determining the factors that influence the stability of soil macroaggregates and microaggregates at different scales that include the landscape, given the variability of soil stability (Amézketa, 1999; Bird et al., 2007).

Therefore, the study of soil aggregate stability is an essential complement to increasing our understanding of the gully erosion process in drylands, and provides insight into improving the stability of soil aggregates based on practices such as log dams and gully channel vegetation that can result in enhanced soil resistance to erosion (Frankl et al., 2021; Guo et al., 2018; Wang et al., 2021). Gully erosion still requires extensive research oriented to its prevention, mitigation, reduction, and rehabilitation at the landscape scale (Mararakanye and Sumner, 2017), to conserve soil structure and primary soil ecosystem services (Faucon et al., 2017) in these fragile landscapes (Sidle et al., 2019).

It is important to acknowledge that in our study area, the variables characterized at the landscape scale appeared to have a greater influence than those at the local scale, suggesting that hillslope processes may be influencing gully activity to a higher degree than processes within the gullies. This knowledge could inform restoration strategies and the establishment of measures for soil erosion control. However, there may be cases where landscape and local scale variables interact with one another. In some instances, some of these variables can be relevant for gully initiation (i.e., landscape scale variables) and others for determining gully development (i.e., local scale variables and soil aggregate scale). Thus, integrating different scales can result in effective management practices by maintaining or increasing site productivity.

5. Conclusions

This work shows the seminal multiscale role of soil aggregate stability in a region severely affected by gully erosion. It adds to knowledge of this “keystone soil property” in these degraded semi-arid systems and its relationship with variables at local and landscape scales. Macroaggregates and microaggregates were more stable at headscarps than at gully bottoms, where soil aggregates exhibited lowest stability. The high stability found in headscarps is related to vegetation surrounding gully banks and ground cover in the hillslopes. Unstable aggregates at the gully bottoms may increase gully depth, and trigger tunneling and undermining. The interactions between local and landscape scale variables are evident in the study area and serve to explain soil aggregate stability. The main variables related to soil macroaggregate stability in the headscarps are ground cover and terrain attributes. Sidewall soil macroaggregate stability is related to profile curvature, distance to farm dams, and gully depth and width. The macroaggregate stability of gully bottoms is related to gully depth, terrain curvature, and drainage area. For soil microaggregate stability in headscarps, ground cover, terrain attributes, and gully width were the most related variables. At sidewalls, microaggregate stability is related to terrain attributes, distance to catchment outlet, ground cover, and the longitudinal morphology of the drainage line. Terrain attributes, distance to farm dams and roads, gully depth, and width are related to microaggregate stability in gully bottoms. These are the key functional elements influencing erosion within gullies and the conditions at the landscape scale associated with soil aggregate stability, which is essential for assessing gully erosion and understanding water flux dynamics triggering soil erosion in gully channels. We demonstrate the importance of considering local scale variables (within gullies) and hillslopes (landscape scale) in aggregate stability to contribute in more detail to the changes in soil structure. This knowledge can provide insights into current and future gully growth patterns resulting from differential soil aggregate stability and interactions with local and landscape variables, both natural and human-originated. A foundation for soil management and conservation or restoration in similar gullied systems in semi-arid areas should focus on the variables that can be manipulated by human intervention and include: a) maintaining average hillslope ground cover of 20 %, b) vegetation on gully walls and drainage lines, and c) farm dams at least 290 m from gullies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2022.106864.

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