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The indirect impact of encroaching trees on gully extension: A 64 year study in a sub-humid grassland of South Africa

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ABSTRACT

Gully erosion and woody plant encroachment are frequently observed in grasslands worldwide. Gully erosion driven by water processes is usually affected by topography, land-use change and vegetation cover. We hypothesised that trees, through their potential link with overland and subsurface flow, may have an impact on gully extension. However, very few studies have simultaneously considered tree encroachment and gullies. We used aerial photographs to study *Acacia sieberiana* encroachment and gully erosion in a South African grassland (KwaZulu-Natal Province) for a period lasting 64 years. At the catchment scale, results showed that acacias started invading after 1976 and transformed the grassland into a savanna with 9.45% of tree cover in 2009. Gully area increased by 3.9% in the last 64 years and represented 12.76% of catchment area in 2009. Mean estimated sediment loss was 200 Mg ha^{-1} of gully y^{-1}, indicating a high erosion rate mainly due to the collapse of gully banks after swelling and shrinking. Volumetric retreat rate (V) of 15 gully heads was correlated with drainage area (*Drain.A*) by a power function explaining 64% of the variance: $V = 0.02 * Drain.A^{0.83}$. A positive correlation between gully retreat rate and *Acacia* canopy area was measured between 2001 and 2009 when established tree encroachment was observed. These results, associated with the susceptibility of this soil to subsurface flow and the observation of pipe erosion systems in the field, showed that both surface and subsurface processes occur in this sub-humid grassland and that trees can be indirectly associated with increased gully erosion.

1. Introduction

Gully formation is a widespread natural erosion phenomenon that induces significant soil losses, with both ecological and economic consequences (Bull, 1981; Lal, 1998; Poesen et al., 2003; Valentin et al., 2005). Gullies are found in a large variety of landscapes, from arid areas (e.g. Ward et al., 2001) to cultivated lands and grasslands. The factors controlling gully erosion are numerous, including bedrock type, soil type, topography, soil surface features, and vegetation cover associated with climatic conditions, especially rainfall intensity and alternation of wet and dry seasons (Imeson and Kwaad, 1980; Poesen et al., 2003). Anthropogenic factors commonly include land-use change (Ward et al., 2001) and activities associated with road and construction sites as well as animal pathways (Valentin et al., 2005).

The understanding of gully initiation (threshold determination) and gully evolution (driving factors) is still debated with many methodological advances in recent years (Martínez-Casasnovas, 2003; Vandekerckhove et al., 2003). Further research is needed, especially with regard to the ways in which environmental changes affect gully erosion (Poesen et al., 2003). Previous studies often highlighted the importance of land-use changes associated with vegetation cover on processes affecting gully erosion (Chaplot et al., 2005; Muñoz-Robles et al., 2010; Vandekerckhove et al., 2000; Ward et al., 2001). Most often, dense vegetation cover reduces runoff susceptibility (Böhm and Gerold, 1995; Molina et al., 2007; Podwojewski et al., 2011; Schlesinger et al., 1990) by intercepting rainfall and limiting soil crusting (Podwojewski et al., 2008). Lower runoff results in a lower concentration of water and flow shear stress which in turn limits the formation of gullies (Poesen et al., 2002). Several authors have provided examples in sub-Saharan Africa where a decrease of vegetation cover induced an increase of gully erosion (e.g. Boardman et al., 2003; Frankl et al., 2011).

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Sub-humid grasslands in KwaZulu-Natal province of South Africa, even with their dense grass cover, suffer from severe gully erosion (Sonneveld et al., 2005). Gullies in South Africa are typical of the Drakensberg (mountain) foothills of KwaZulu-Natal. Gullies were already present 1000 years ago (Botha et al., 1994) and are mainly controlled by the distribution of rainfall (Yaalon, 1987) and intrinsic factors such as bedrock types, terrain morphology and bioclimatic zones (Botha, 1996). The colluvial unconsolidated sediments accumulated in this region are very prone to erosion (Rienks et al., 2000) and to piping (Beckedahl, 1998), which has often been associated with gully erosion (Bryan and Jones, 1997; Faulkner et al., 2008; Sonneveld et al., 2005; Valentin et al., 2005). Piping, considered as subsurface erosion, can be formed by concentrated water flow in soils (often associated with a sharp transition between two soil horizons). The collapse of the pipe roof is common as well as the breaching of deeper horizons, which eventually results in deep gullying.

Another phenomenon affecting grasslands worldwide is woody plant encroachment. Woody plant encroachment has been observed in grasslands and savannas for approximately 150 years (Van Auken, 2009). Tree roots may bind the soil, preventing soil erosion. However, woody encroachment in grasslands has been associated with higher intensities of inter-rill erosion in semi-arid areas (Petersen and Stringham, 2008) and with higher gully extension (Martin and Morton, 1993). This was claimed to be due to higher runoff associated with reduced grass cover under trees. Trees can also increase ecosystem evapotranspiration (Scott et al., 2006), increase water infiltration by stemflow (Dunkerley, 2002; Mauchamp and Janeau, 1993), possibly move water from deep soil layers to shallower and dryer soil layers by hydraulic lift (Ludwig et al., 2003), and modify subsurface water flow (Huxman et al., 2005; Liang et al., 2009). As gully erosion is also linked to subsurface water flow, in particular through piping (Faulkner et al., 2004; Planchon et al., 1987), trees may have an impact on gully erosion either through surface or subsurface water processes. However, little is known about the effects of tree encroachment on gully erosion. Muñoz-Robles et al. (2010) who tested this hypothesis could not show that eroded gully volume was related to woody vegetation cover in Australia.

The two objectives of this study are to analyse (i) the long-term evolution of gully extension and woody plant encroachment over a period of 64 years in a sub-humid grassland of South Africa using a time-series of aerial photographs and (ii) the main factors affecting gully head extension, including woody vegetation cover in the drainage areas of 15 selected gully heads.

2. Materials and methods

2.1. Study site

The study site is located in South Africa where both gully erosion and woody plant encroachment are severe, particularly in the KwaZulu-Natal province. For approximately 30 years, trees have been encroaching in savannas and sub-humid grasslands in the area probably due to grass cover degradation (by frequent fires or increases in cattle numbers), which is among the main factors favouring germination of tree seedlings (Grellier et al., 2012). The communal grassland of Potshini village, in the foothills of the Drakensberg mountains, 8 km south of Bergville (28° 48′ 37″ S; 29° 21′ 19″ E), has been studied for 10 years (Fig. 1). It is representative of the upper part of the Thukela river basin with a 30,000 km² catchment. We focused our research on a 2.5 km^2 sub-catchment of the grassland (from 1452 to 1217 m a.s.l.) which presents wide and deep gullies and tree encroachment.

The climate of this area is characterized as subtropical sub-humid with summer rainfall (Schulze, 1997). The mean annual precipitation is 750 ± 162 mm (data from 1945 to 2009). The average annual temperature is 13 °C (Schulze, 1997). This site is classified as grassland biome by Mucina and Rutherford (2006). The specific biome is the Northern KwaZulu-Natal moist grassland, usually dominated by *Themeda triandra* and *Hyparrhenia hirta* (Mucina and Rutherford, 2006). The encroaching trees, *Acacia sieberiana* var. *woodii* (Burtt Davy) Keay & Brenan, are indigenous. The geology of the site is characterized by fine-grained sandstones, shales, siltstone and mudstones of the Beaufort and Ecca Groups of the Karoo Supergroup that alternate in horizontal succession (King, 2002). Unconsolidated colluvial polycyclic deposits up to 15 m thick from the Pleistocene fill the valleys and are very prone to linear gully erosion (Botha et al., 1994). Soil types are Acrisols upstream and Luvisols downstream (FAO/ISRIC/ISSS, 1998) with two main soil horizons: a 40 cm thick A horizon and a B horizon generally occurring between 40 and 90 cm depth. The topsoil is cohesive with dark grayish brown color (10YR 4/1 to 10YR 4/3); it has a sandy loam texture with 10–20% clay, with many fine and medium roots and with evidence of considerable biological activity (termites, dung beetles, earthworms). The B horizon is darker and very cohesive and hard. Clay, mainly illite, accumulates in this B horizon up to 50%. Soils are not sodic but have pipe erosion systems, first reported by Henkel et al. (1938).

2.2. Data collection and processing

Monthly rainfall data were collected from 1940 to 2002 at the Bergville weather station (South African Weather Service) located 8 km north of the catchment. Rainfall was collected from 2003 to 2009 at the weather station of the Potshini catchment.

A digital elevation model (DEM) of 5 m cell size and a vertical error of less than 1 m was created from a combination of 6000 points obtained in 2009 by a differential global positioning system (DGPS) with 10 cm accuracy on average in x, y, z, covering half of the catchment and from pre-existing contour data from the center for National Geospatial Information (NGI, Department of Land Affairs, South Africa).

Non-georeferenced aerial photos dated 1945, 1962, 1976 and 1985 and completed with two orthorectified aerial photographs from 2001 and 2006 were obtained from the NGI (Table 1). A more recent view of the area (May 2009) was obtained from a series of digital airborne images collected using a small, low speed, remotely controlled unmanned aerial vehicle (UAV) called Pixy (Asseline et al., 1999). The digital camera used was a Canon EOS450D with a focal length of 34 mm to cover the area with 18 images. The images were taken from an altitude of 150 m.

Orthorectification was performed on all non-georeferenced photographs using ERDAS Imagine 9.1 (Erdas, Leica 2006). The DEM and the 2006 orthorectified image (the most spatially and radiometrically accurate image) were used for orthorectification. Between 53 and 113 ground control points (GCP) per image equivalent to 1–5 GCP per km^2 (except for 2009, cf. below) were used. The 18 images from the 2009 Pixy survey were also orthorectified in ERDAS Imagine 9.1 using the DEM and 400 DGPS GCP (equivalent to 160 GCP per km^2) surveyed in the field during image capture. These points were highly visible features that could be identified on the imagery, and were surveyed with an overall accuracy of ± 5 cm.

Gully length and area as well as tree cover (density and canopy area) were mapped for the whole watershed (manually digitized in ArcGIS 9.3, ESRI, 2008) for the six periods between 1945 and 2009. In order to highlight a possible relationship between trees and gully extension, as well as to understand which topographic/geomorphological parameters influence gully extension, 15 active gully heads were selected in the catchment (Fig. 2). Arc Hydro Tools (implemented in ArcGIS 9.3) was used to compute drainage area of each gully head (*Drain.A*, m^2) for the six time periods. Gully length (*GL*, m), gully head area (*GHA*, m^2), retreat length (*RL*, m y^{-1}) and retreat area (*Retreat.A*, m^2 y^{-1}) of 15 active gully heads were measured and calculated for the six above-mentioned time periods in ArcGIS 9.3. We also calculated the canopy area of large trees (> 15 m^2) and the canopy area of medium trees (between 1 and 15 m^2) for each drainage area for the six time periods.

Other topographic factors were measured for 2006–2009 (when an accurate DEM was available) using ArcGIS 9.3 for the 15 gully heads: