Catena 98 (2012) 110–119

Contents lists available at SciVerse ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

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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ARTICLE INFO

Article history:
Received 21 July 2011
Received in revised form 29 June 2012
Accepted 1 July 2012
Available online xxxx

Keywords:
Acacia sieberiana
Aerial photographs
Erosion
Soil piping
Subsurface
Gully threshold

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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doi:10.1016/j.catena.2012.07.002

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:

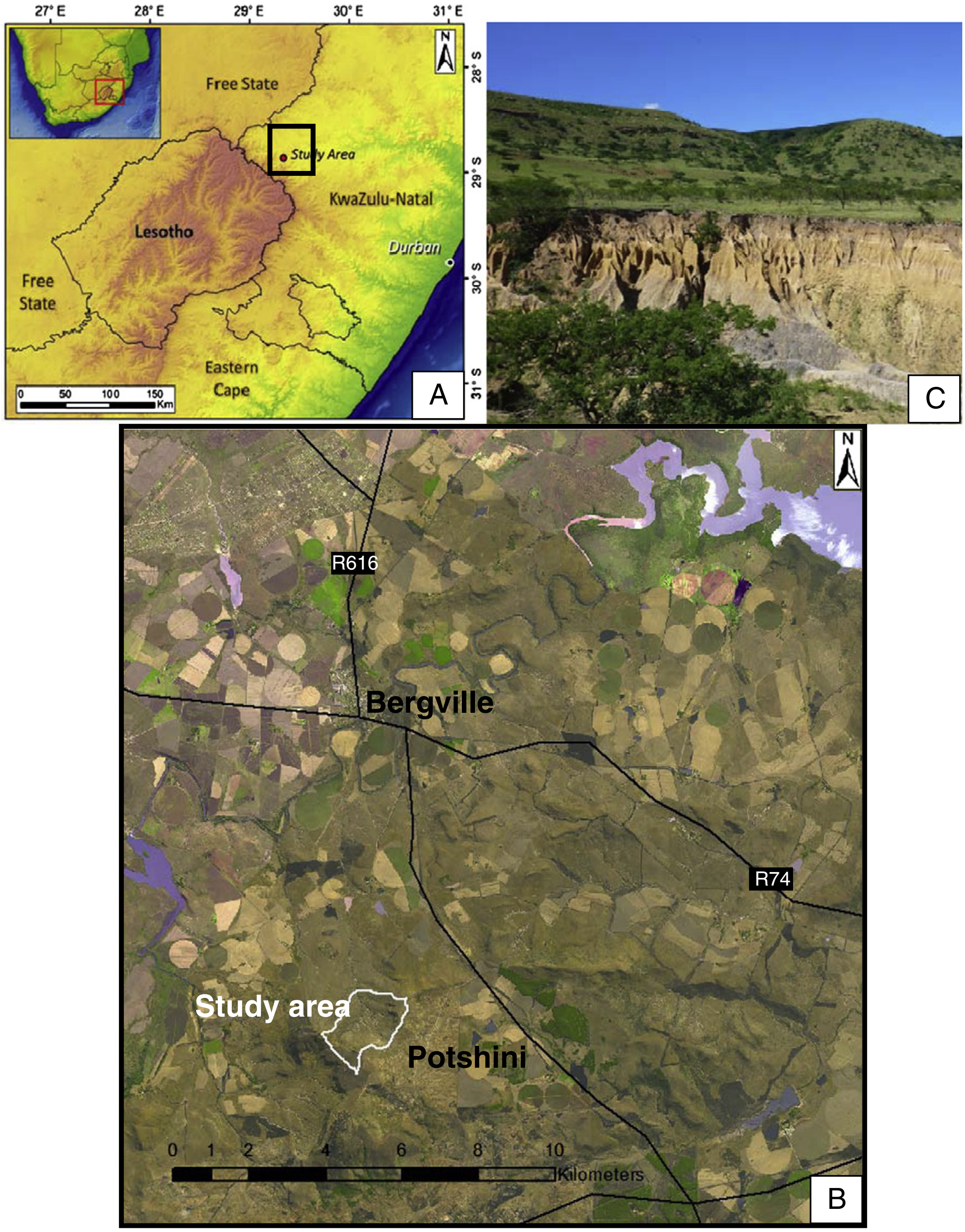

Fig. 1. Localization of the study site (A) with an aerial picture of 2008 (B) and a photograph of a gully and the encroachment in the catchment (C).

drainage average slope (*DAslope*) of each drainage area, local gully head slope (*LHS*), and Stream Power Index (*SPI*) of each drainage area. *SPI* is a measure of the erosive power of the water flowing over a specific area (Bull, 1979; Moore et al., 1993). In order to compare our values with those from other recent studies (Kakembo et al., 2009), we applied the following formula (Beven and Kirkby, 1979):

$$SPI = \ln\left(\frac{Drain.A_c}{L} \times \tan(\beta)\right)$$

where β is the local head slope (radiant), $Drain.A_c$ is the current drainage area of the gully head (m^2) and L is the gully length (m) delimiting $Drain.A_c$ at its lowest section (cf. Fig. 3).

The volumetric retreat rate (V, $m^3\,y^{-1}$) was calculated for each gully head by multiplying the accurately measured *Retreat.A* (as described previously) with field measurements along transects where we measured the width and the depth every 20 m along the longitudinal development of the gully. The number of measurements depended on gully size. We hypothesised that the studied gully heads did not expand in depth in the last 64 years as the colluvia had been strongly eroded and gullies have almost all reached the hardest sandstones of the horizontal layer of parent rock. The same gully depths were thus used for all studied periods. We used the method described by Vandekerckhove et al. (2000) and the above-mentioned measurements to calculate gully volumes (*GVol*).

Table 1
Properties of aerial photographs used in this study. All photographs were taken in the dry season.

Date	Scale	Focal length (mm)	Resolution (cm)	Source	Root mean square error (RMSE, m)
1945	1:20000	177.8	100	NGI	3.00
1962	1:30000	152.83	250	NGI	0.21
1976	1:30000	151.86	250	NGI	12.23
1985	1:30000	152.63	250	NGI	0.31
2001	1:30000	153.692	75	NGI	5.00
2006	1:30000	153.69	75	NGI	5.00
2009	1:25000	18	18	Pixy*	2.6

NGI: National Geospatial Information, Department of Land Affairs, South Africa.
* Small, low speed, remotely controlled unmanned aerial vehicle (UAV) (Asseline et al., 1999).

2.3. Statistical analyses

All statistical analyses were done with R software 2.13.2 (R Development Core Team, 2011). Variables were $\log_{10}$ transformed when necessary to ensure homogeneity of variance and normality of residuals. Pearson's correlations between rainfall and tree canopy area or gully retreat rate were used for the study at the catchment scale.

For the study of the 15 gully heads we first analyzed the six periods together (with $n = 15*6 = 90$) in order to take into account the effect of rainfall on gully retreat area. We used a multiple regression with a mixed effect model ("lme" R procedure, taking into account the temporal pseudo-replication) to study whether the rain, the drainage area (*Drain.A*) and tree canopy area (tall tree canopy area: "*Tree*" and medium tree canopy area) were correlated to *Retreat.A* and *V* between 1945 and 2009.

We next analyzed the data over three periods and for the last 3 years as follows:

1) 1945–1975: absence of trees;
2) 1976–2000: beginning of tree encroachment;
3) 2001–2009: establishment of tree encroachment;
4) 2006–2009: last period where we could also measure topographic parameters and where tree encroachment was at its maximum.

Fig. 2. Aerial view of the catchment (white line boundary) in 2006 with the delimited gully system in transparent white and the 15 selected gully heads (in black with white contours).

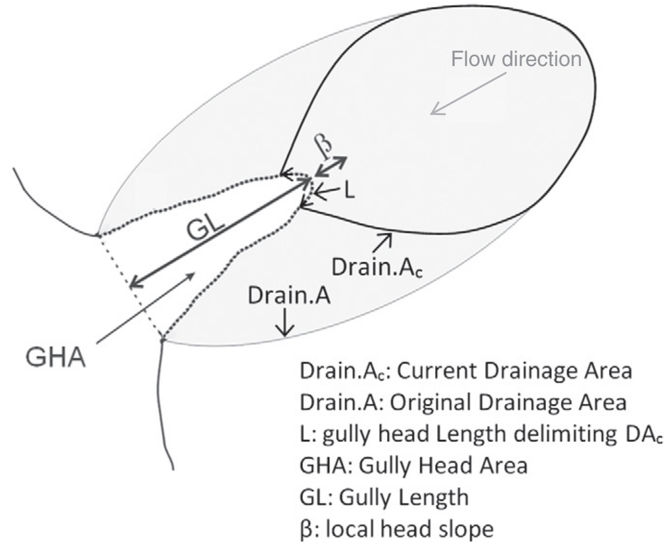

Fig. 3. Schematic representation of the parameters used for *SPI* calculation.

For the three first periods, we tested for a relationship between *Drain.A* and tree canopy area on *Retreat.A* and *V* with multiple regressions (linear models, "lm" R procedure; because the comparison of "lm" and "lme" models indicates that the pseudo-replication effect was negligible). For the last period 2006–2009, we also tested for an effect of *Drain.A*, *DAslope*, *SPI* and tree canopy area on *Retreat.A* and *V* with multiple regressions (linear model "lm" R procedure).

3. Results

3.1. Woody plant encroachment over 64 years at the catchment scale

The area occupied by *A. sieberiana* increased during the study period from 1945 to 2009 when it covered 9.45% of the catchment area (Fig. 4). Tree density started to increase slowly after 1976 and encroachment was clearly observed after 2001 (Fig. 4). Tree canopy area increased by 10-fold in 35 years. This increase followed the same trend as large tree density which represents the largest portion of woody cover area. Large trees

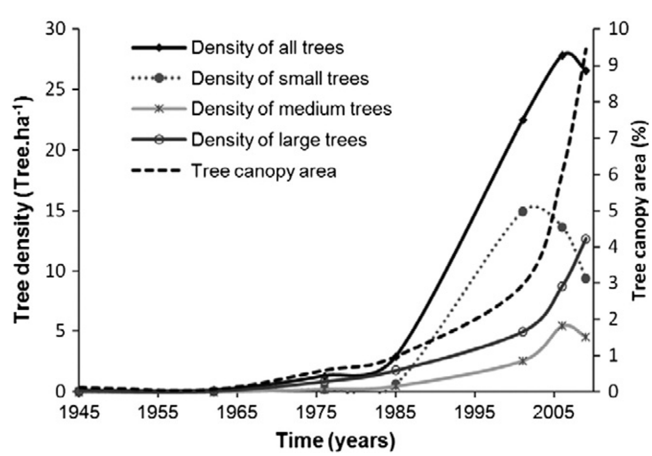

Fig. 4. Smoothed tree density and tree canopy area in the catchment from 1945 to 2009. Small trees (canopy area < 1 m^2), medium-sized trees (1 m^2 < canopy area < 15 m^2), large trees (canopy area > 15 m^2).

(>15 m^2 canopy area) covered 8.73% of the catchment area in 2009. In comparison, medium-sized trees (1 m^2<canopy area<15 m^2) covered 0.71% of the catchment area in 2009. In 2009 a peak of encroachment occurred with a maximum density of trees (28 trees ha^{-1}). The density of large trees increased in 2009 while the density of medium-sized and small trees (canopy area<1 m^2) decreased mostly because they grew into large and medium-sized trees respectively and they were less supplemented with new tree growth (Fig. 4).

The mean rainfall for each period showed an increase from 1945 to 2009 from 752 mm y^{-1} to 906 mm y^{-1}. Considering each period ($n=6$), a positive Pearson correlation between mean rainfall and tree canopy area was found ($R^2=0.81$, $p=0.014$).

3.2. Gully extension rate over 64 years at the catchment scale

From 1945 to 1975, gully retreat area remained constant at the catchment scale, with a value of 950 m^2 y^{-1}. Between 1976 and 1984, gully retreat area increased up to 2300 m^2 y^{-1} and stayed stable until 2001. A second increase was observed in the period 2001–2005 and reached 4000 m^2 y^{-1}. Finally, in 2009, gully retreat area continued to increase, reaching 4441 m^2 y^{-1}. Since 1945, gully area increased by 3.9%, reducing the grazing surface in the grassland. A significant positive Pearson correlation was found between rainfall and gully retreat area ($R^2=0.67$, $p=0.04$) at the catchment scale.

To compare our results with other studies, we converted retreat area (m^2 y^{-1}) into Mg of sediment per hectare of gully surface per year (Martínez-Casasnovas, 2003) or gully erosion rate. The estimation of sediment produced by gullies was computed assuming a minimum bank gully height of 3 m (based on field observations), a bulk density of 1.4 g cm^{-3} which was the mean across three soil profiles in the catchment from 0 to 120 cm and a total gully surface of 31.9 ha in the study site in 2009. The estimated total retreat area between 1945 and 2009 was 1530 m^2 y^{-1}, which gives a mean of 200 Mg ha^{-1} y^{-1}.

3.3. Analyses of the extension of 15 selected gully heads

The different measured topographic parameters were very diverse among the gully heads (see Table 2 for an example in 2006–2009). Mean retreat length of the 15 gully heads varied between 0.23 m y^{-1} in 1945–1961 (data not shown) and 0.77 m y^{-1} in 2006–2009 (Table 2). One gully had a maximum retreat length in 2006–2009 of 1.67 m y^{-1} (Table 2). The mean (±SD) over the 64 years was 0.40±0.32 m y^{-1}.

Because medium-sized tree canopy areas were not significantly correlated with retreat area or volumetric retreat rate for any of the studied periods, we only present results with tall tree canopy areas (*Tree*). For the 6 periods taken together (1945–2009), rainfall, *DA*, and *Tree* were all significant factors in the multiple regression, as were *Retreat.A* and *V* (Table 3).

The results of the analyses by periods were similar for *Retreat.A* and for *V* with a slightly better fit of each model with *V* (Table 4). For each studied period, *Drain.A* significantly affected *Retreat.A* and *V* (Table 4). *Drain.A* was significantly related to *Retreat.A* and *V* by a power function: *Retreat.A* (or *V*) = a**Drain.A*^{b}. As an example, we show that *Drain.A* explained 61% and 66% respectively of the variance over the entire period from 1945 to 2009 (Fig. 5). For the shorter period 2006–2009, *Drain.A* explained lower percentages of the variance of *Retreat.A* and *V* with 23% and 36%, respectively (Fig. 5). The *b* parameter showed a decrease with time for both variables *Retreat.A* and *V* (Table 4). The *b* values of the equation with *V* ranged from 0.91 (in 1945–1975, $R^2=0.53$) to 0.64 (in 2006–2009, $R^2=0.36$) with a global value of 0.83 for the 64 years of study (1945–2009, $R^2=0.64$).

The variable *Tree* included in the multiple regression was significant only for the last period 2001–2009 when we observed a clear tree encroachment in the grassland (Table 4). In the 2001–2009 period, *Tree* and *Drain.A* were negatively correlated. *Tree* had higher values for smaller drainage areas (cf. Fig. 5). For this reason, we tested the relationship between *Tree* and *Retreat.A* (and *V*) by dividing both variables by *Drain.A* (using a linear model). *Tree* was still positively correlated to *Retreat.A* and *V* (with a slightly higher R^2). We present here the results of the regression between *V* and *Tree*: $R^2=0.42$, $p=0.0002$ associated with the following equation ($n=29$):

$$\frac{\ln(V)}{\ln(Drain.A)} = 0.86 \times \frac{\ln(Tree)}{\ln(Drain.A)} + 0.84$$

Similar results were observed in 2006–2009 with a higher contribution of *Tree* on *Retreat.A* and *V*. *DAslope* and *SPI* in the multiple regression in 2006–2009 were not significantly correlated to *Retreat.A* or to *V* and were excluded from the model.

4. Discussion

4.1. Gully and woody plant encroachment evolution at the catchment scale over 64 years

The encroachment rate found in this study falls within the range of worldwide studies but is at the lower end of those values (Table 5). The values of encroachment rate in the various cited studies are rarely

Table 2
Topographic parameters measured for the 15 gully heads in 2009: drainage area (*Drain.A*, m^2), drainage average slope (*DAslope*, %), local gully head slope (*LHS*, %), stream power index (*SPI*), gully length (*GL*, m), gully head area (*GHA*, m^2), and gully volume (*GVol*, m^3). Parameters measured for the last period (2006–2009): retreat length (*RL*, m y^{-1}), retreat area (*Retreat.A*, $m^2.y^{-1}$) and volumetric retreat rate (*V*, m^3 y^{-1}). Means and standard deviations (SD) are displayed below.

Gully number	*Drain.A* (m^2)	*DAslope* (%)	*LHS* (%)	*SPI*	*GL* (m)	*GHA* (m^2)	*GVol* (m^3)	*RL* (m y^{-1})	*Retreat.A* (m^2 y^{-1})	*V* (m^3 y^{-1})
1	41,258	28.4	17.3	3.78	120	4844	7673	0.67	68.6	218
2	85,597	29.4	30.1	5.39	225	11,695	28,096	0.33	202.0	727
3	8490	12.1	10.2	3.05	98	2258	2090	1.33	56.3	150
4	10,5150	30.9	12.2	3.83	218	8101	53,650	0.33	56.6	358
5	26,467	18.8	6.4	2.26	143	4175	22,030	0.33	14.6	69
6	13,054	18.8	12.9	3.56	68	875	1998	0.33	4.0	11
7	17,412	26.7	13.9	3.82	69	809	1459	0.67	19.0	64
8	14,350	17.7	8.8	4.78	71	1393	1875	1.33	38.6	122
9	103,776	24.2	10.0	1.89	240	12,008	79,928	1.33	163.6	1303
10	3701	12.9	8.7	1.69	65	1795	4235	0.67	52.6	266
11	2790	9.1	5.4	0.79	57	555	423	0.33	15.0	17
12	57,941	30.4	9.1	4.14	63	1196	4429	1.00	33.0	157
13	38,924	28.2	7.1	3.17	132	3585	23,642	1.67	113.0	897
14	9240	36.4	15.7	3.30	73	1292	2995	0.67	43.6	156
15	3039	10.5	12.2	1.87	64	911	1922	0.67	35.0	123
Mean	35,412	22.3	12.0	3.20	113	3699	15,763	0.77	61.0	309
SD	36,336	8.6	6.0	1.05	64	3881	23,140	0.44	56.5	374

Table 3
Multiple regression (linear mixed effect model) of gully head retreat area (*Retreat.A*, $m^2.y^{-1}$) and volumetric retreat rate (*V*, $m^3.y^{-1}$) relative to rainfall, drainage area (*Drain.A*, m^2) and tall tree canopy area (*Tree*, %) over 64 years ($n=15*6=90$).

Ln(*Retreat.A*) =	2.73 ln(*Rainfall*)	+0.54 ln(*Drain.A*)	+0.092 ln(*Tree*)	−20.09
p value	0.0173	0.0001	0.0097	0.0124
Ln(*V*) =	2.63 ln(*Rainfall*)	+0.80 ln(*Drain.A*)	+0.10ln(*Tree*)	−20.51
p value	0.0221	<0.0001	0.0063	0.0116

above 1% y^{-1}. In our study, the only case reported over 1% y^{-1} matched an area already encroached at the beginning of the study and where large trees, capable of reproduction, could accelerate the encroachment. If we only refer to the surface occupied by tree canopies, the grassland we studied still has a large potential for encroachment with only 9.45% of area covered by trees in 2009. Despite a slight decrease in the total tree density in the last few years (since 2006), the population is probably not yet at equilibrium because the density of large trees is still increasing. These large trees are the biggest seed producers. After 2006, inter-tree competition may have taken place as well as changes in other disturbance factors such as herbivory and fires, which can modify tree populations (Grellier et al., submitted for publication; Sankaran et al., 2005; Ward, 2005). Unfortunately we have very little data about these factors during the study period.

Few studies (Goslee et al., 2003) have indicated that encroachment was not correlated with rainfall, but many others (Ansley et al., 2001; Sankaran et al., 2005; Widenmaier and Strong, 2010) indicated that rainfall was an important factor of tree population density in grassland. Rainfall played an important role in this sub-humid system but is probably not the sole cause of expansion of *A. sieberiana* in our study site. Cattle density has increased in tandem with the human population in the last few years (pers. comm. from the local Potshini community). The local human population uses trees as fuel, which would limit encroachment by tree cutting. Contrastingly, cattle should increase encroachment through grazing (which increases the space available for tree germination) and seed dispersal in the grassland (Van Auken, 2009).

The high gully erosion rate of 200 Mg ha^{-1} y^{-1} found for this area is in the range of the erosion rates of badlands in France (Bufalo and Nahon, 1992; Descroix and Olivry, 2002) or of badlands in the Barasona reservoir basin in Spain with 302–455 Mg ha^{-1} y^{-1} (Martínez-Casasnovas and Poch, 1998). However, our estimated rate is much higher than those referenced in Poesen et al. (2003), where rates ranged from 0.1 to 64.9 Mg ha^{-1} y^{-1}. This erosion rate was also very high compared to the estimated values given by Chaplot et al. (2011) of 4.8 Mg ha^{-1} y^{-1} at our study site but at a smaller spatial scale (1 m width bank gully) and for a time period of 45 min during a single rainfall simulation. Chaplot et al. (2011) showed that 62% of total soil loss was due to runoff, 24% to splash erosion and only 13% to collapse of aggregates on the gully bank. This last-mentioned process may however play a more important role in gully erosion of this area. Three months after the rainfall simulation, an important part of the 1 m-wide gully bank collapsed (pers. obs.), which was mainly due to swelling and shrinkage of clay. Over 64 years of study, loss of similar entire blocks has often occurred and is related to the succession of dry and wet seasons. The large difference between the erosion rate of 4.8 Mg ha^{-1} y^{-1} estimated from a short rainfall event and the amount of 200 Mg ha^{-1} y^{-1} estimated after 64 years of observation suggests the importance of bank erosion due to swelling and shrinkage processes in the gully erosion of this area. A similar result has been reported in Tunisia (De Ploey, 1974). This high erosion rate does not actually reflect the soil loss exported from the catchment to an outlet reservoir because of short-distance deposits in such deep and large gullies (Imeson and Kwaad, 1980; Rieke-Zapp and Nichols, 2011). Once the gully bank falls into the bottom of the gully, the surface exposed to rainfall is large and is not covered by vegetation. Removal and deposition of sediment downstream is thus easier (Podwojewski et al., 2011), as we observed in the field in rehabilitated zones filled by sediment inside the gullies.

Humid regions usually have higher rates of gully retreat than arid regions (Poesen et al., 2003; Samani et al., 2010). This is consistent with the significant correlation found in this study between rainfall and gully retreat area or volumetric retreat rate for the 64 year study. Gully erosion increases significantly with rainfall >40 mm day^{-1} (Bouchnak et al., 2009), or >25 mm h^{-1} (Rieke-Zapp and Nichols, 2011).

4.2. Environmental parameters and gully head retreat

4.2.1. Drivers of gully erosion, surface runoff, subsurface flow and piping

The retreat length of the 15 selected gully heads in this area (mean of 0.40 m y^{-1}) is comparable to those measured by other authors. Martínez-Casasnovas (2003) recorded values of 0.7–0.8 m y^{-1} at gully heads. Burkard and Kostaschuk (1997) found over a period of 62 years high values between 0.97 and 3.64 m y^{-1} on average, with a maximum at 33.39 m y^{-1}. Samani et al. (2010) found 0.2 m y^{-1} in an arid area in Iran (mean annual rainfall = 273 mm), whereas in Belgium (mean annual rainfall = 750 mm), Nachtergaele et al. (2002) reported an average value of 1.8 m y^{-1}. The drainage area is hydrologically linked to gully erosion as it represents the surface available for water runoff which concentrates at a specific point where a gully can be created (Schumm, 1979). Drainage area can also reflect the subsurface water that reaches the gully (Sneddon et al., 1988). The importance of the drainage area on gully erosion has been shown by several authors (Burkard and Kostaschuk, 1997; Stocking, 1980; Vandekerckhove et al.,

Table 4
Simple regressions of retreat area (*Retreat.A*) and volumetric retreat rate (*V*) against drainage area (*Drain.A*) for the three studied periods as defined according to encroachment state in the grassland. Multiple regressions with *Drain.A*, tall tree canopy area (*Tree*), slope of drainage area (*DAslope*) and stream power index (*SPI*) for the three studied periods and for the last period 2006–2009 explaining *Retreat.A* and *V* are also presented. "na" means non-available, "ns" means non-significant and "nu" means not used. * indicates that 1 or 2 samples have been removed due to leverage, causing distortion in model validation. *DAslope* and *SPI* are not displayed because they were not significant.

	n	*Retreat.A* ($m^2.y^{-1}$)	*Drain.A* (m^2)	*Tree* (%)	*n*	*V* ($m^3.y^{-1}$)	*Drain.A* (m^2)	*Tree* (%)
1945–1975	28*	ln(*Retreat.A*) = −4.53	+0.65 ln(*Drain.A*)		28*	ln(*V*) = −5.71	+0.91 ln(*Drain.A*)	
p value			0.0001	na			<0.0001	na
R^2			0.44				0.53	
1976–2000	30	ln(*Retreat.A*) = −2.77	+0.57 ln(*Drain.A*)		30	ln(*V*) = −3.92	+0.82 ln(*Drain.A*)	
p value			<0.0001	ns			<0.0001	ns
R^2			0.50				0.62	
2001–2009	29*	ln(*Retreat.A*) = −1.68	+0.51 ln(*Drain.A*)		29*	ln(*V*) = −2.81	+0.76 ln(*Drain.A*)	
p value			0.0007	nu			<0.0001	nu
R^2			0.32				0.46	
2001–2009	29*	ln(*Retreat.A*) = −1.55	+0.76 ln(*Drain.A*)	+0.62 ln(*Tree*)	29*	ln(*V*) = −2.84	+1.12 ln(*Drain.A*)	+0.82 ln(*Tree*)
p value			<0.0001	0.0020			<0.0001	0.0002
R^2 and partial R^2		0.53	0.32	0.21		0.69	0.46	0.23
2006–2009	14*	ln(*Retreat.A*) = −0.77	+0.93 ln(*Drain.A*)	+1.18 ln(*Tree*)	15	ln(*V*) = −2.69	+1.33 ln(*Drain.A*)	+1.38 ln(*Tree*)
p value			0.0005	0.0022			<0.0001	0.0005
R^2 and partial R^2		0.69	0.23	0.46		0.78	0.36	0.42

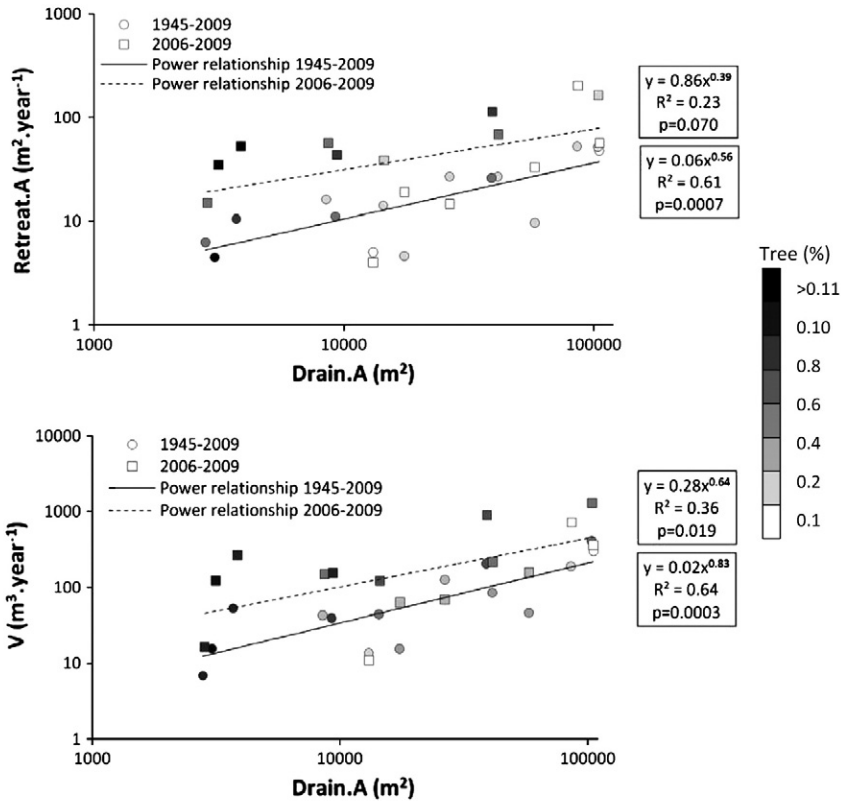

Fig. 5. Power relationship between drainage area (*Drain.A*, m^2) and retreat area (*Retreat.A*, $m^2.y^{-1}$) and between *Drain.A* and volumetric retreat rate (*V*, $m^3.y^{-1}$) for the entire period 1945–2009 ($n=15$) and for a shorter period (2006–2009) ($n=15$). Tree canopy areas (*Tree*, %) located in each drainage area are displayed using grey shade. Power curves are linearised through the use of a logarithmic scale.

2000) and is confirmed by the results obtained in this study with high correlations observed between retreat area ($m^2\ y^{-1}$), or volumetric retreat rate ($m^3\ y^{-1}$) and the drainage area for all periods. Different values of the parameter b from the power relationship have been reported in the literature for both components (*Retreat.A* or *V*). For volumetric retreat rate, Vandekerckhove et al. (2000) found $b=0.59$ ($R^2=0.66$) for a data set grouping two sites and 55 gullies. When considering a smaller sample size and each site separately, Vandekerckhove et al. (2000) obtained values of b up to 0.72 ($R^2=0.71$). This last-mentioned result is closer to what we found in this study for *V*. The results obtained with *Retreat.A* ($b=0.56$, $R^2=0.61$) over 64 years in our study are very similar to those presented by Burkard and Kostaschuk (1997) over 62 years with $b=0.59$ ($R^2=0.77$). The decrease of b values over the study period for *Retreat.A* and for *V* is probably linked to the length of each period. The first period was 30 years, the second, 14 years and the last period, 8 years. Vandekerckhove et al. (2003) showed that b values increased from short term to the long term. This explains the higher b values in this study for the first period of 30 years, decreasing for the second period and then for the third period. The role of the drainage area became more pronounced at the longer time scale (Vandekerckhove et al., 2003). This is partially due to a better representation (lower variability) of the measurements of eroded volume or retreat area in the long term. Extreme erosion events (especially those due to falling of entire blocks which are independent of runoff discharge and thus of drainage area) are averaged in the long run. The second explanation is based on a higher occurrence of extreme rainfall events at the long time scale: the drainage area plays an important role during these events by producing runoff and eventually inducing higher erosion rates.

Correlations between retreat area or volumetric retreat rate and drainage area indicate that gully erosion in this watershed are at least partially due to waterfall erosion (fall of surface runoff in the gully head) as shown by Stocking (1980), and confirmed by our direct observations in the field during a strong rainfall event. These correlations have also been observed when seepage erosion induced by subsurface interflow was active (Sneddon et al., 1988). These correlations tend therefore to suggest that gully erosion is induced by both surface and subsurface processes.

Table 5
Comparison of global mean tree encroachment rates (ER) in grasslands or savannas.

Authors' name	Location	Study period	ER (% y^{-1})	Commentaries
Coop and Givnish, 2007	Caldera Valley. New Mexico. USA	1935–1996	0.3	
Robinson et al., 2008	Pilbara, Western Australia	1943–2001	0.4	
Goslee et al., 2003	Southern New Mexico	1936–1996	0.7	
Archer et al., 1988	South Texas	1941–1983	0.5	
Ansley et al., 2001	Southwestern USA	1976–1995	2.2	Untreated area
Ansley et al., 2001	Southwestern USA	1976–1995	1.1	Tree-cleared area in 1976
Roques et al., 2001	Swaziland	1947–1990	0.7	
Hudak and Wessman, 2001	Madikwe, South Africa	1955–1996	0.7	
Wigley et al., 2009	Hlabisa (Hluhluwe), South Africa	1937–2000	1.0	
Laliberte et al., 2004	Southern New Mexico	1937–2003	0.2	
This study	Drakensberg foothills South Africa	1945–2009	0.27	Considering encroachment starting in 1976

In 2006–2009, the lack of correlation between erosion rates and other topographic factors linked to overland flow (slope of drainage areas, stream power index) was associated with a weaker correlation with drainage area. We suggest that, for this short period at least, subsurface processes may have contributed more significantly than surface processes, as observed by Imeson and Kwaad (1980). Almost all studies have related gully headcut retreat to surface runoff parameters (Poesen et al., 2003; Valentin et al., 2005). Only a very few studies considered or tested subsurface hydrological processes, such as piping (Beckedahl, 1998; Crouch, 1983; Imeson and Kwaad, 1980; Planchon et al., 1987; Rienks et al., 2000; Valentin et al., 2005). Pipes are not always apparent from the surface and therefore not easily followed or localized and associated with gullies. In the study area, there was evidence of piping at different locations due to the collapse of their surface roofs (Fig. 6). Pipes are specifically formed in these soils due to (i) the difference in permeability between A and B horizons (Beckedahl, 1998; Verachtert et al., 2010), (ii) the association of soil shrinkage, inducing cracks where water concentrates, and (iii) the presence of a dispersive C horizon (Imeson and Kwaad, 1980). The four pipes represented in Fig. 6 are probably linked to each other and suggest that it should be subsurface water draining to the gully. The upstream shift of the gully head erosion can be accelerated by the presence of upstream pipes in the line of the gully head (Rienks et al., 2000; Sonneveld et al., 2005). Pipes can be localized and mapped from collapsed soil depressions visible from the surface (Verachtert et al., 2010). The mapping of pipes is a methodological challenge, which was only partially achieved in this study. Field evidence and previous non-significant correlations with surface water related factors suggest that subsurface processes are very likely to affect this area together with surface processes.

4.2.2. Impact of trees on gully erosion

Positive correlations between retreat area or volumetric retreat rates and tall tree canopy area only started to be significant for the period 2001–2009 when a sufficient area was covered by trees. In previous studies, when vegetation cover was related to gully erosion, it was mainly through surface water processes: high grass cover decreases runoff and decreases gully erosion (Graf, 1979; Muñoz-Robles et al., 2010). In specific areas, trees have been shown to decrease grass cover under their canopies and then increase runoff (Petersen and Stringham, 2008). However, it is not always the case because trees can also decrease runoff through litter input which protects the soil against splash effects (Descroix et al., 2001) or through the increase of under-canopy vegetation and roots (Pierson et al., 2010). A specific survey on grass cover in the study area showed that the herbaceous biomass was similar under tree canopies and in the open grassland (Grellier et al., submitted for publication). We hypothesise that runoff should not differ significantly under canopies and between canopies. Surface water processes may thus not be significantly influenced by trees in this grassland.

Two hypotheses can be formulated from our results.

1) Impact of trees on subsurface processes: trees have been shown to increase infiltration by stemflow (Dunkerley, 2002; Levia and Frost, 2003; Liang et al., 2009) and to modify subsurface water flow (Huxman et al., 2005; Liang et al., 2009). Stemflow infiltrates into the soil and can reach great depths by preferentially following tree roots (Johnson and Lehmann, 2006; Martinez-Meza and Whitford, 1996). As stemflow increases with canopy size (Martinez-Meza and Whitford, 1996), sufficient tree canopy area could favour water infiltration at the catchment scale. In our study, the abundance of large trees in the upper part of the catchment may enhance this mechanism. Sonneveld et al. (2005) mentioned that in specific cases (especially in soil experiencing piping), infiltration could stimulate subsurface erosion and retreat rate of down-slope gully heads. An increase of subsurface water may increase the swelling of clays. This may be followed by shrinkage during dry periods. Strong desiccation favours cracks and bank erosion from gully head walls (De Ploey, 1974). Erosion rates might thus increase with higher tree canopy area through the effects of stemflow and piping. This scenario needs to be further investigated.
2) Impact of subsurface water on tree establishment in grassland: we also propose that trees may only be a marker or indicator of the presence of subsurface water which could then induce higher gully erosion rates for the reasons mentioned above (piping or intense subsurface flow activity). Indeed, trees establish in an environment with specific conditions, among which water availability is essential (Miller and Halpern, 1998; Shrestha et al., 2003; Wu and Archer, 2005). Soil properties, linked to water availability, are a strong determinant of tree establishment in grassland (Grellier, 2011; Robinson et al., 2008; Schleicher et al., 2011). *A. sieberiana*, for example, is a species that grows better in riparian areas (Timberlake et al., 1999). We suggest that trees could have established better (and then developed larger tree canopy areas) in areas where subsurface water was easily accessible and more abundant (such as preferential drainage channels which can evolve in pipes). In both hypotheses, trees are indirectly linked to gully erosion through active subsurface processes.

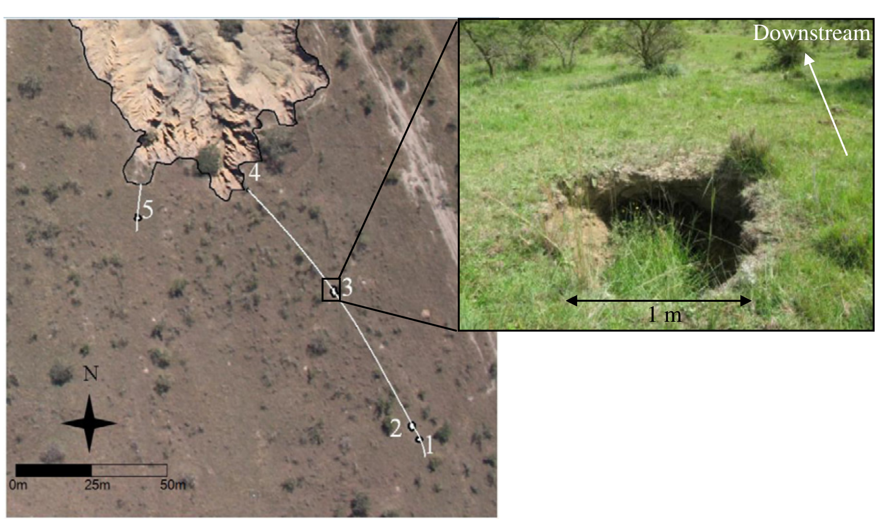

Fig. 6. Aerial view of a gully head in 2009. Numbers 1–5 represent pipes (white circle with black perimeter) visible from the soil surface. Pipe number 4 is located at the gully head and is probably the exit of the system starting with pipe number 1. The zoomed area is a photograph of pipe number 3 in the wet season.

5. Conclusions

- This study confirms that erosion processes and mechanisms depend on the spatial and temporal scale of the study. At the small temporal scale (one rainy season or one rainfall simulation), or at the small spatial scale (the plot scale, often studied), processes linked to rill and gully erosion are mostly observed as surface processes: splash detachment, soil surface crusting and runoff depend mostly on rainfall characteristics and vegetation cover. At larger spatiotemporal scales, other processes can be observed, such as piping or bank erosion that are highly variable in space and time.
- Our results suggest that the gullies in this sub-humid grassland were highly affected by both surface and subsurface water processes.
- Trees are statistically associated with increasing gully erosion. This counter-intuitive relationship can be due to the facts that (i) trees increase subsurface flow, (ii) and/or trees establish in areas of high subsurface flow (such as piping) that in turn increases gully erosion.
- If the indirect impact of trees on gully extension through the increase of subsurface flow is confirmed at a longer time scale, this would have an implication in the management of grasslands where gullies are present and where tree encroachment is not controlled. Tree thinning might thus be considered.

Acknowledgment

The authors would like to thank the University of KwaZulu-Natal, the Institute of Research and Development (IRD), for infrastructure and financial support. DW thanks the NRF for funding. We further thank the community of Potshini for sharing their land as well as the National Geo-spatial Information of the Rural Development and Land Reform department of South Africa for providing the aerial pictures. A special thank go to Jean Asseline and Jean-Louis Rajot for their “pixy” experience.

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