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Influence of vegetation distribution on sediment yield in forested marly gullies

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Abstract

The cover provided by forest vegetation makes it possible to fight erosion efficiently. Furthermore, vegetation barriers can also play a major role by trapping eroded sediments and thus vegetation located downslope of a gully can be important. The objective of this study is to highlight the role of vegetation distribution in a marly gully in reducing sediment loss at the outlet. To do this, sediment yield in gullies with similar geological and geomorphological components, but with different vegetation cover and distribution, was studied for 2 years. Sediment traps installed at gully outlets permitted the distinction of active gullies from inactive ones. The results show that gully activity is not correlated with the percentage of total vegetation cover, but with the percentage of cover of low vegetation in the gully floor. This is due to sediment trapping processes and highlights the importance of the spatial distribution of forest vegetation in reducing sediment yield at the gully outlet. Thus, gullies with similar total vegetation cover can have very different activities, and inactive gullies exist that are only partially covered with vegetation. Inactive gullies with as low as 33% vegetation cover occur where vegetation is mainly present in the gully floor. The results also show that above 50% cover of low vegetation in the gully floor as a percentage of the gully floor surface, gullies are generally inactive.
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Keywords: Erosion; Marls; Gully; Forest vegetation; Vegetation distribution; Sediment trapping

1. Introduction

Forest vegetation is an efficient mean of combating erosion: it protects soils against erosive agents (e.g. Bochet et al., 1998; Martinez-Mena et al., 1999), regulates hydrological regimes (e.g. Dunne et al., 1991; Bergkamp et al., 1996; Solé-Benet et al., 1997;

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Cerdà, 1998a) and improves the soil physical and chemical properties (e.g. Bochet et al., 1998, 1999). Consequently, vegetation cover is important for soil protection. Studies have shown that erosion generally decreases with increased vegetation cover (Snelder and Bryan, 1995; Morgan et al., 1997; Cerdà, 1999).

In France, studies have been carried out on erosion on marly lands and on the influence of vegetation. Some studies have shown that erosion is about 1 cm $year^{-1}$ in bare zones (Richard and Mathys, 1999; Lecompte et al., 1998; Rovéra et al., 1999). Ablation of marls happens during winter due to gelifraction, leading to sediment accumulations on slopes. Part of these sediments collects in the gully floor due to gravity and overland flow during low rainfall events. Heavy rainfall events then transport these sediments to the gully outlet. Headwater erosion in basin streambeds is also responsible for sediment destabilisation on slopes. These combined processes maintain bare gullies, where vegetation is generally unable to settle.

The experimental catchment basins of Draix (Alpes-de-Haute-Provence, France) have made it possible to make a comparison over 15 years of the erosive behaviours of two torrential marly basins with different vegetation covers (Richard and Mathys, 1999). The Brusquet basin, with a surface area of 108 ha, was reforested at the end of the nineteenth century, primarily with Austrian black pine (*Pinus nigra* Arn. subsp. *Nigra*), and it now has a vegetation cover of 87%. Its general slope, surface area and lithology characteristics are similar to those of the Laval catchment basin (86 ha) which was not reforested and now has natural vegetation cover of 32%. When erosional losses from these two basins are apportioned to the bare areas, the sediment yield is some 40 times lower in the forested Brusquet basin.

Although this contrast may partly reflect lithological differences, studies elsewhere have demonstrated the effectiveness of gully vegetation in trapping eroded material (Sanchez and Puigdefabregas, 1994; Meyer et al., 1995; Dabney et al., 1995, 1999; Cammeraat and Imeson, 1999). Van Dijk et al. (1996) and Lee et al. (1999, 2000) showed that there is a filtration effect of flows through vegetation with sediment deposited as a result of a reduction of transport energy. Deposits were then observed upslope of vegetation barriers, on steeper slopes than those without vegetation (Takken et al., 1999; Bochet et al., 2000). Consequently, great quantities of eroded sediments are trapped and do not reach the catchment outlet (Beuselinck et al., 2000). In forested marly basins in France, Rey (2002) has observed that coarse sediments can be trapped by vegetation barriers during rainfall periods, forming sediment deposits upslope of vegetation.

Thus, the spatial distribution of forest vegetation in a gully may be significant in reducing erosional losses from gullies, and vegetation located downslope of an eroded zone may therefore play a prominent role. The objective of this study is to highlight this hypothesis. To do this, erosive activity of gullies with similar geological and geomorphological characteristics, but with different vegetation components, have been studied for 2 years.

2. Materials and methods

Observations were carried out on 37 gullies located in four catchments in the French Southern Alps: the Saignon and Naples catchments in the Grand Vallon area, and the

Francon and Brusquet catchments in the Haute-Bléone area (Alpes-de-Haute-Provence) (Fig. 1). Thirteen gullies were studied the first year; the choice of these gullies was random. The second year, we continued to study these 13 gullies; we also started studying 24 other gullies not completely covered with vegetation but with apparently low sediment yield.

The catchments have been restored with technical engineering within torrents; thus, headwater erosion has been stopped at the base of the gullies. Vegetation was mostly established by bioengineering works within gullies, permitting vegetation establishment on gully slopes and floor. Vegetation is now primarily made up of Austrian black pine and common pine (*Pinus sylvestris*) for the trees, of whitebeam (*Sorbus aria*) and opalus maple (*Acer opalus*) for the shrubby layer, of restharrow (*Ononis fruticosa*) for the under-shrubby layer, finally, of calamagrostide (*Calamagrostis argentea*) for the herbaceous layer.

The 37 gullies ranged in area from 246 to 6267 m^2. All the gullies were located on black marls. Average gully side slopes ranged from 65% to 120% and gully floor slopes from 20% to 56%; thus, the geomorphological characteristics of the gullies were not precisely alike. Some studies showed that topography is an important factor for sediment deposition, so that not all the sediments eroded within a catchment reach the outlet, even in the absence of vegetation (Desmet and Govers, 1995; Cerdà, 1998b; Beuselinck et al., 1999, 2000; Steegen et al., 2000). However, in these gullies mentioned in the literature, depositions of eroded material have been observed on gentle slopes of less than 10%. In our marly gullies, deposition of eroded materials can be observed on gentle slopes during low rainfall events, even without vegetation. Yet, in our context of high slopes, gully floor observations carried out at the annual scale in unvegetated gullies showed that after heavy rainfall events, nearly all the sediments deposited in gully floor are transported and reach the gully outlet (Ollivier and Pinatel, 2000). So, at the annual scale, topography does not seem to be a prominent factor for sediment deposition.

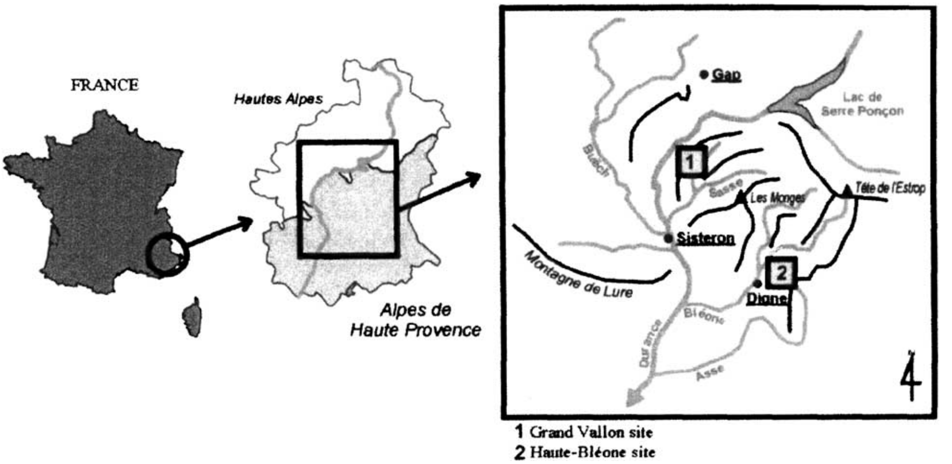

Fig. 1. Location of the field sites.

Vegetation maps—with interfluve and gully floor lines—were established to a scale of 1:5000th and digitised on an Arc-Info/Arc-View GIS for each of the 37 gullies. Total vegetation covers varied from 33% to 78% and the maps provided information on vegetation distribution. This was characterised by distinguishing four vegetation layers: arborescent, shrubby, under-shrubby and herbaceous (e.g., Fig. 2). "Low vegetation", possibly responsible for sediment trapping, was represented by the under-shrubby and herbaceous layers. Arborescent and shrubby layers corresponded to the "aerial vegetation cover". Gullies were also divided in two parts: gully slopes and gully floor. From field observations, gully floors were defined as zones of 1-m width. To represent the gully floor width, an Arc-Info "buffer" function of 0.5 m was performed around the floor lines. Then, a second map was established with six groups: cover of low vegetation in the gully floor, cover of low vegetation on gully slopes, aerial vegetation cover in the gully floor, aerial vegetation cover on gully slopes, gully bare floor and gully bare slopes (e.g., Fig. 3). Cover percentages were then established for each group.

Two recording rain gauges installed in Grand Vallon and Haute-Bléone areas were used to obtain the rainfall hyetograms. Measurements of sediment yield at all gully outlets were carried out for each rainfall event, by the means of sediment traps (Fig. 4), composed of plastic boxes perforated with 10-mm diameter holes on the downstream side, thus making it possible to retain coarse materials while allowing to water pass through. The boxes, with a unit capacity varying from 30 to 70 l, were laid out in cascade, in order to multiply the total capacity of material retention. Wooden planks were used to channel flows along the traps. Cement was used to level and consolidate the ground upstream of the traps, in order to avoid undermining problems. This measurement system made it possible to collect essentially coarse sediments. Suspended materials in transit with water were not taken into account. In other studies, Richard and Mathys (1999) showed that, on the scale of the gullies studied here, the suspended sediments theoretically represent about 15% of the total load. Although Dabney et al. (1995) and Beuselinck et al. (2000) showed that vegetation is more likely to trap finer sediments, other studies (Meyer et al., 1995; Cammeraat and Imeson, 1999; Lee et al., 1999, 2000; Rey, 2002) showed that coarse sediments could also be trapped by vegetation barriers. Thus, sediment yield of gullies measured with these sediment traps made it possible to study the effect of vegetation in trapping coarser eroded sediments.

Measurements for 2 years permitted determination of whether the studied gullies produced sediments. For some very active gullies, the sediment traps were not big enough to trap all the eroded sediments; it was thus not possible to study relationships between increasing vegetation cover and decreasing erosion. However, it was possible to determine gully activity. Gullies were classified into two groups, active and inactive on the basis of sediment yield. Fifteen gullies, which produced some sediment, were classified as active and twenty-two which produced none as inactive. The influence of five vegetation components on gully activity was then studied: the total vegetation cover; the cover of low vegetation; the cover of low vegetation on slopes; and the cover of low vegetation in the gully floor: for each of these the vegetation cover was expressed as a percentage of the total surface area of the gully; the fifth study concerned the cover of low vegetation in the gully floor as a percentage of the total surface area of the gully floor.

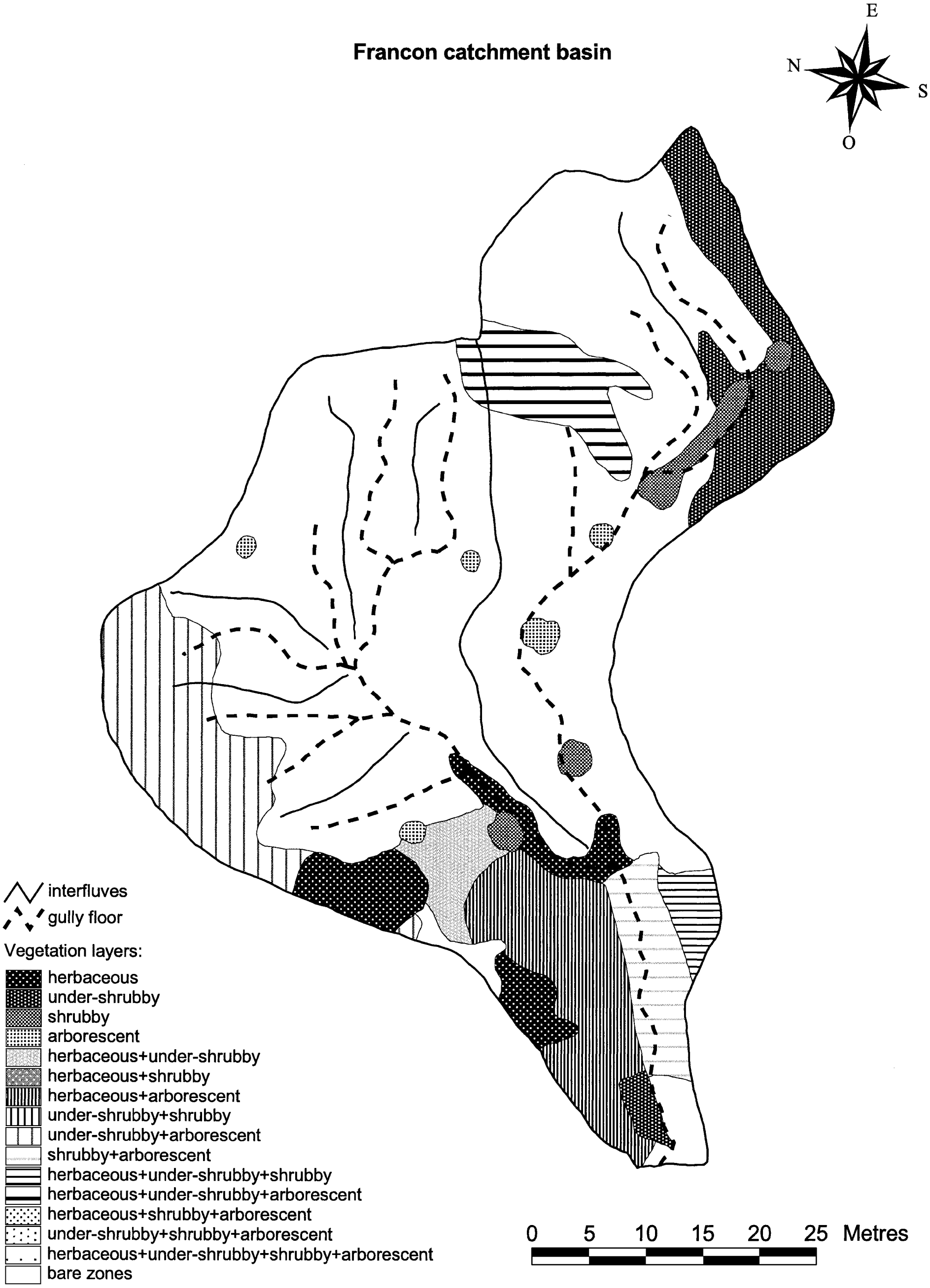

Fig. 2. Vegetation map of gully *E*.

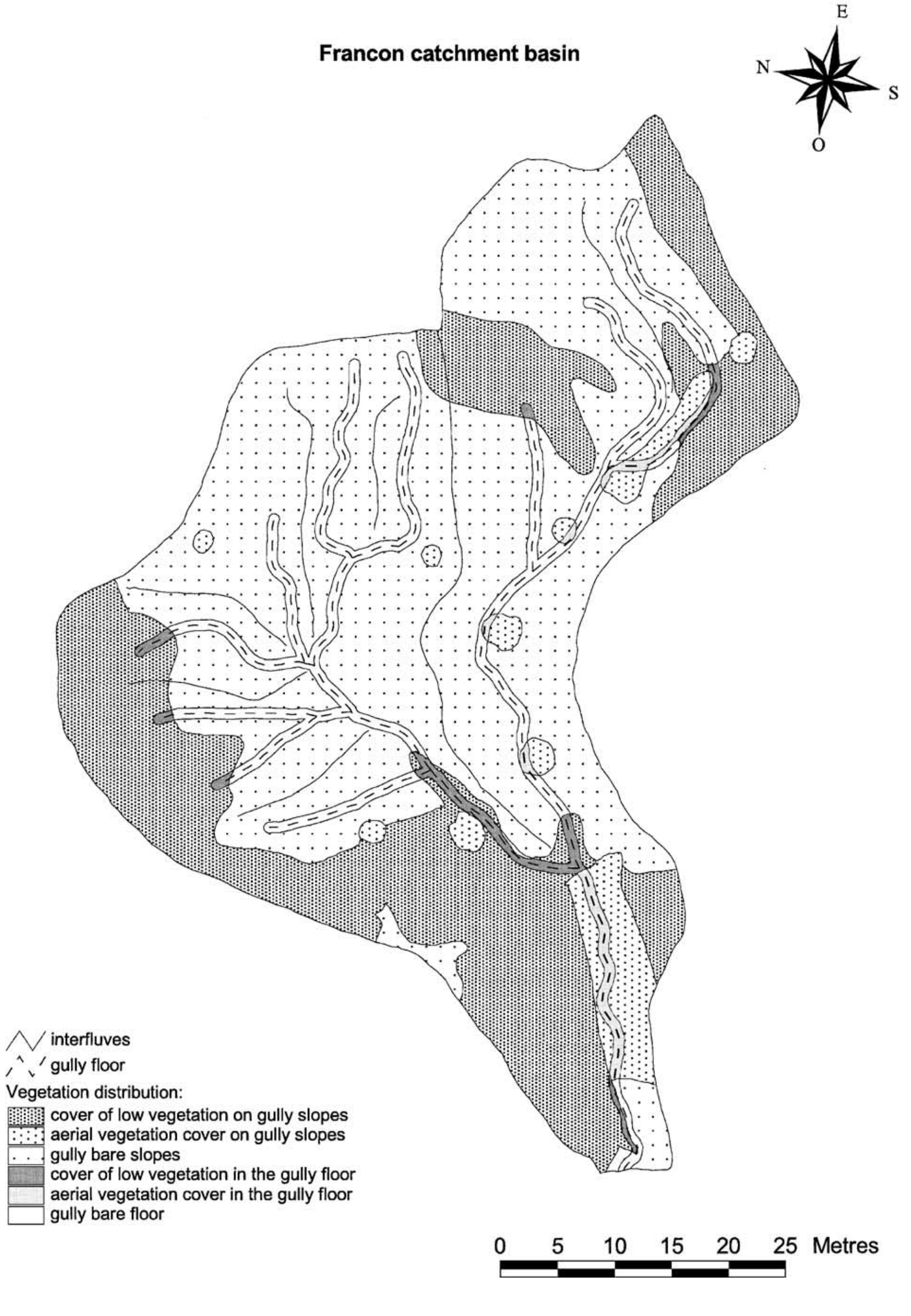

Fig. 3. Vegetation distribution map of gully *E*.

Fig. 4. Sediment trap with a capacity of 500 l.

The influence of these components was studied with a nonparametric test on the sum of ranks: the Mann–Whitney *U*-test. This test gives a critical probability (cp) for verification of the H_0 hypothesis according to which two populations—the active and inactive gullies—are identical in view of vegetation components.

Table 1
Rainfall characteristics observed in 1999 and 2000

Basin	Total rainfall (mm)		Most extreme rainfalls			
	1999	2000	1999		2000	
			During 24 h (mm 24 h^{-1})	During 1 h (mm h^{-1})	During 24 h (mm 24 h^{-1})	During 1 h (mm h^{-1})
Saignon	865	977	55	9	85	35
Naples	–	977	–	–	85	35
Francon	1026	1144	110	22	61	26
Brusquet	–	1071	–	–	57	20

Table 2
Gully characteristics and sediment yield (extended to the total surface area of the gully) in the Grand Vallon area

Basin	Saignon															Naples						
Gully name	G	H	I	J	K	L	M	a	b	c	d	e	f	g	h	i	j	k	v	w	x	y
Observation dates	1999–2000							2000								2000						
Gully surface area (m^2)	2502	2306	2798	3834	1760	2542	2284	373	995	611	843	808	574	830	434	2582	1957	2037	5202	2433	6267	849
Gully side average slope (%)	100	90	110	120	100	100	100	90	100	100	75	120	100	90	100	90	65	90	90	100	75	90
Gully floor average slope (%)	35	24	42	38	34	36	33	37	38	37	29	51	55	38	37	25	40	40	48	46	34	29
Total vegetation cover (as a percentage of the total surface area of the gully)	66	61	64	72	57	54	48	53	43	77	35	42	42	40	60	54	54	44	62	58	43	45
Cover of low vegetation (as a percentage of the total surface area of the gully)	29	61	47	35	41	45	23	23	41	74	31	40	16	19	54	29	27	29	44	22	29	17
Cover of low vegetation on slopes (as a percentage of the total surface area of the gully)	26	57	42	31	37	42	22	21	38	67	28	34	11	16	49	25	23	25	41	19	28	14
Cover of low vegetation in the gully floor (as a percentage of the total surface area of the gully)	3	4	5	4	4	3	1	2	3	7	3	6	5	3	5	4	4	4	3	3	1	3
Cover of low vegetation in the gully floor (as a percentage of the total surface area of the gully floor)	43	50	35	80	40	50	13	14	33	64	27	43	56	50	63	67	100	67	75	50	100	27
Sediment yield ($t\ ha^{-1}\ yr^{-1}$)	6.3	0	*3.2*	*3.9*	*17.2*	*6.3*	*8.8*	0	0	0	*8.1*	*9.5*	0	*1.4*	0	0	0	0	0	0	0	0

Table 3
Gully characteristics and sediment yield (extended to the total surface area of the gully) in the Haute-Bléone area

Basin	Francon						Brusquet								
Gully name	A	B	C	D	E	F	l	m	n	p	q	r	s	t	u
Observation dates	1999–2000						2000								
Gully surface area (m^2)	818	511	1281	1792	3366	2392	317	678	2221	302	570	2412	964	551	246
Gully side average slope (%)	90	75	90	100	75	100	65	65	90	100	90	90	75	65	90
Gully floor average slope (%)	55	29	46	56	26	49	20	25	30	42	29	37	39	32	31
Total vegetation cover (as a percentage of the total surface area of the gully)	78	70	44	44	38	41	40	33	47	33	44	51	62	49	49
Cover of low vegetation (as a percentage of the total surface area of the gully)	43	69	38	33	33	18	28	26	30	25	31	37	54	44	39
Cover of low vegetation on slopes (as a percentage of the total surface area of the gully)	34	66	36	31	32	17	21	20	27	18	24	29	46	34	25
Cover of low vegetation in the gully floor (as a percentage of the total surface area of the gully)	9	3	2	2	1	1	7	6	3	7	7	8	8	10	14
Cover of low vegetation in the gully floor (as a percentage of the total surface area of the gully floor)	75	27	22	14	11	11	71	50	43	78	54	80	89	100	74
Sediment yield ($t\ ha^{-1}\ yr^{-1}$)	0.3	*9.5*	*16.4*	*10.2*	*3.7*	*6.3*	0	0	0	0	0	0	0	0	0

3. Results

The results presented here correspond to measurements in 1999 and 2000. On the whole, 27 rainfall events led to some filling of the sediment traps. The rainfall characteristics observed during the two observation years appear in Table 1, and Tables 2 and 3 present the gullies characteristics and sediment yield. For some active gullies, sediment traps occasionally overflowed during major rainfall events; sediment yield values of the overflowed traps appear in italics in the table. The values indicated may therefore underestimate the actual sediment loss. Moreover, lack of knowledge about the suspended materials may explain certain low values of sediment yield. The relations between the

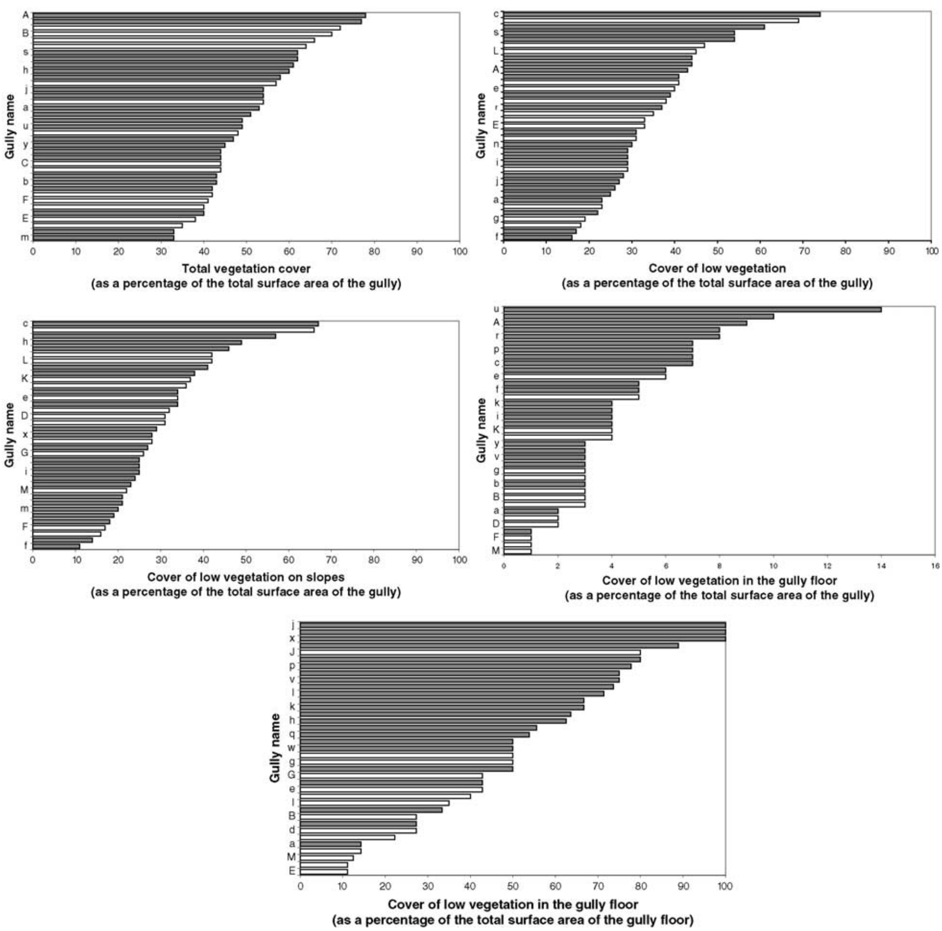

Fig. 5. Relations between gully activity and the vegetation components (in grey: inactive gullies; in white: active gullies).

Table 4
Results of the Mann–Whitney *U*-test

Relations	Critical probability (cp) for H_0 hypothesis
Gully activity and total vegetation cover (as a percentage of the total surface area of the gully)	0.7928
Gully activity and cover of low vegetation (as a percentage of the total surface area of the gully)	0.7222
Gully activity and cover of low vegetation on slopes (as a percentage of the total surface area of the gully)	0.3441
Gully activity and cover of low vegetation in the gully floor (as a percentage of the total surface area of the gully)	0.0036
Gully activity and cover of low vegetation in the gully floor (as a percentage of the total surface area of the gully floor)	0.0016

gully activity and the vegetation components are represented on Fig. 5. Table 4 gives the results of the Mann–Whitney *U*-test.

4. Discussion

The results of the test confirm the findings illustrated in Fig. 5. They show that gully activity is correlated with the cover of low vegetation in the gully floor, as a percentage of the gully surface area (cp = 0.0036) or of the gully floor surface area (cp = 0.0016). The main explanation for these results is that sediments eroded on bare surfaces on slopes are trapped and retained by vegetation located in the gully floor. Sediment trapping processes by vegetation barriers have been observed in gully floor within inactive gullies with only partial vegetation cover. Important sediment accumulations were observed upslope of vegetation barriers. In particular, the heaviest rainfall event in the Saignon catchment led to strong erosion on bare zones and eroded sediment deposits up to 7 cm were observed in gully floor upslope of vegetation barriers, on slopes greater than 20%. In other gullies, in the same conditions but without vegetation, such deposits were not observed. Observations also showed that if the vegetation barrier width extends from one gully bank to the other, trapping is effective and sediments are permanently retained. Thus, all the sediments eroded within a gully do not reach the gully outlet. Some trenches carried out in gully floors upslope of vegetation barriers revealed deposits of movable sediments—coming from erosion on slopes and transported by flows—, sometimes on more than 1-m thickness on bedrock. They also showed that these trapped sediments could then be permanently fixed and retained by plant roots. These deposits have only been observed where the vegetation barrier is present across the entire gully floor width. Where this is not the case, sediments may pass around the vegetation barrier.

By contrast, the results show that there is no relationship between gully activity and cover of low vegetation on slopes (cp = 0.3441). Trapping processes have however been observed on slopes (Rey, 2002), but the sediment retention by vegetation may only be temporary. One explanation could be that continuity of the vegetation barrier may be a significant factor in sediment trapping efficiency, as stated by Meyer et al. (1995) and Bochet et al. (2000) who showed that plant morphology is important, i.e. plant species play a prominent role, or Van Dijk et al. (1996) and Lee et al. (1999) who showed that trapping effectiveness increases with strip width. Thus, it appears that vegetation should necessarily constitute a barrier that cannot be circumvented by flows.

The results also show that there is no relationship between gully activity and, respectively, total vegetation cover (cp = 0.7928) and cover of low vegetation (cp = 0.7222).

These results highlight the importance of the spatial distribution of vegetation. The main consequences are that gullies with similar vegetation cover may have very different activities, and that inactive gullies exist that are only partially covered with vegetation. Observations make it possible to identify thresholds of vegetation components for gully activity or inactivity. Thus, the results show that inactive gullies with only 33% vegetation cover exist (gullies *m* and *p*). Vegetation in these gullies is mainly present in the gully floor: vegetation is present in 50% of the floor of gully *m*, and in 78% of the floor of gully *p*. The results also show that gullies are generally inactive above 50% of cover of low vegetation in the gully floor as a percentage of the gully floor surface. Gully *J* is however an exception. Explanation is that in this gully vegetation is localised at the top of the gully floor and bare zones appear at the bottom. Improvement of knowledge is then possible and studies on this topic are in process.

It should be noted that the results correspond to 2 years of measurements. Although heavy rainfall events were observed during the study period, it is possible that more extreme events may occur, re-activating some presently inactive gullies. However, vegetation barriers grow every year and should increase trapping efficiency, as explained by Sanchez and Puigdefabregas (1994) and Dabney et al. (1995).

Finally, attention must be paid to spatial scales (Rey et al., 2002). The effectiveness of sediment trapping by vegetation in gully floor may be dependant on gully size, determining the area of the drainage surface, combined with gully slopes. In this study, the observations were carried out on gullies with maximum areas of about 6000 m^2, under which inactive gullies exist. But in the perennial streams of a catchment basin, vegetation cannot resist to strong hydraulic forces. It would then be interesting to determine drainage surface area thresholds above which sediment trapping becomes ineffective.

5. Conclusion

Vegetation distribution in a gully is important in reducing sediment yield at its outlet; low vegetation in the gully floor traps sediments and thus plays an especially significant role. Studies carried out with the aim of understanding the influence of vegetation cover on the erosive activity of gullies or catchment basins should therefore take vegetation distribution into account. Thresholds of optimal vegetation cover and distribution have been highlighted for explanation of the activity or inactivity of marly gullies.

Better knowledge about relationships between vegetation and erosion could improve erosion models, which often overestimate sediment losses, at the inter-annual or event scales (Takken et al., 1999; Mathys et al., 2000). This is partially due to the fact that vegetation distribution is not taken into account. A statistic and probabilistic model for the evaluation of the inter-annual gully activity is being formulated with the results presented in this study. Studies focussing on relationships between gully activity and vegetation distribution at the scale of individual rainfall events will also be carried out, in order to improve event models.

Finally, results could also be used to set up optimal management of eroded catchment basins (Rey, 2002). As it is not necessary to establish total vegetation cover in a gully to stop the sediment yield at the outlet, cheaper restoration operations could be considered.

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