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The success of recent land management efforts to reduce soil erosion in northern France

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Abstract

Soil erosion is an important problem in open-field agricultural landscapes. With almost no permanent vegetation in small headwater catchments, and with few physical obstacles to reduce runoff velocities, runoff concentration along linear landscape elements (plot boundaries) or thalwegs frequently causes ephemeral gullies to form – the latter reflecting the poor hydrogeomorphic condition of the land- and soilscape. To address this problem, and to remediate negative on- and off-site effects, land management efforts have multiplied over the past decades in many regions. This includes, amongst other measures, the implementation of vegetation barriers called 'fascines'. In the loess-dominated Aa River basin of northern France, where cropland accounts for 67% of the cover, we investigated the effect of fascines on ephemeral gully erosion dynamics, together with rainfall characteristics and cropland management. This was accomplished through a spatially explicit study of 269 sites prone to ephemeral gullying using a diachronic analysis of historical aerial photographs. Between 1947 and 2012, ephemeral gully densities at the scale of the Aa River basin (643 km²) varied between 0.39-1.31 m ha^{-1} (long-term average of 0.68 m ha^{-1} (with local maxima up to 9.35 m ha^{-1}). Densities are, however, much higher when only considering the most erosion-vulnerable municipalities (long-term average of 2.23-4.30 m ha^{-1}); those values should be used when comparing results from this study to other reports of ephemeral gully erosion. Fascines were introduced in 2001 and were present in ~30% of the gully erosion sites by 2012. Although the presence of fascines has an effect on gully length reduction, spatial and temporal variations in gully length were mainly driven by cumulative precipitation. Measurement of sediment deposition at 29 fascines in 2016 showed that only 47% of the fascines functioned as sediment sinks. They stored on average 1.7 Mg of sediment per winter half-year, corresponding to 0.009 Mg ha^{-1}. The results suggest that fascines positively impact the landscape's resilience and reduce ephemeral gully erosion rates. The use of vegetation barriers such as fascines are increasingly implemented for erosion control in western Europe, but pose problems for the management of open-field landscapes.

Key words: Aa River valley; aerial photograph; fascine; ephemeral gully

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1. Introduction

In the open-field agricultural landscapes of Europe, especially in the topographic-rolling loess-covered regions (Haase et al., 2007), soil erosion is an important problem (Delmas et al., 2012). Small headwater catchments in this region have virtually no permanent vegetation and few physical obstacles to reduce runoff velocities, therefore, runoff concentration along linear landscape elements (plot boundaries) or thalwegs frequently causes ephemeral gullies to occur – the latter reflecting the poor hydrogeomorphic condition of the land- and soilscape (Vandaele and Poesen, 1995; Boardman and Poesen, 2006) (Fig. 1A). As discussed by Poesen et al. (1996), ephemeral gullies are temporary erosion features because their small dimensions allows them to be eliminated during tillage. Given no change in management or land use, ephemeral gullies frequently recur at the same locations following heavy precipitation events.

To address this problem, and to remediate negative on- and off-site effects such as topsoil truncation (Pineux et al., 2017), mudflow hazards (Douvinet and Delahaye, 2010; Fig. 1B), floods, and pollution (Boardman et al., 1994; Verstraeten and Poesen, 2002), land management efforts have multiplied over the past decades in many regions (Boardman et al., 2003; Maetens et al., 2012). This includes, amongst other measures, optimizing agronomic techniques and crop rotations (such as no-tillage, mulching, winter cover crops, intercrops), land use conversions (from cropland to pastures), runoff retention pools, check dams in ditches, grass buffer strips (both as grassed waterways and filter strips), and vegetation barriers.

Fascines are any type of linear vegetation barrier consisting of live and/or dead vegetation (Evette et al., 2009; Richet et al., 2016). They differ from hedges in the sense that they were especially conceived to reduce runoff velocities and trigger sedimentation. Many types can be found, including double-rowed willow posts with in-between staples of bundled willow branch cuttings, woven branches along poles, wood chips, straw, or any other organic residue inserted in-between rows of mesh fences. Such barriers are typically implemented on plot boundaries across thalwegs or along topographic contours (Figs. 1C and 1D).

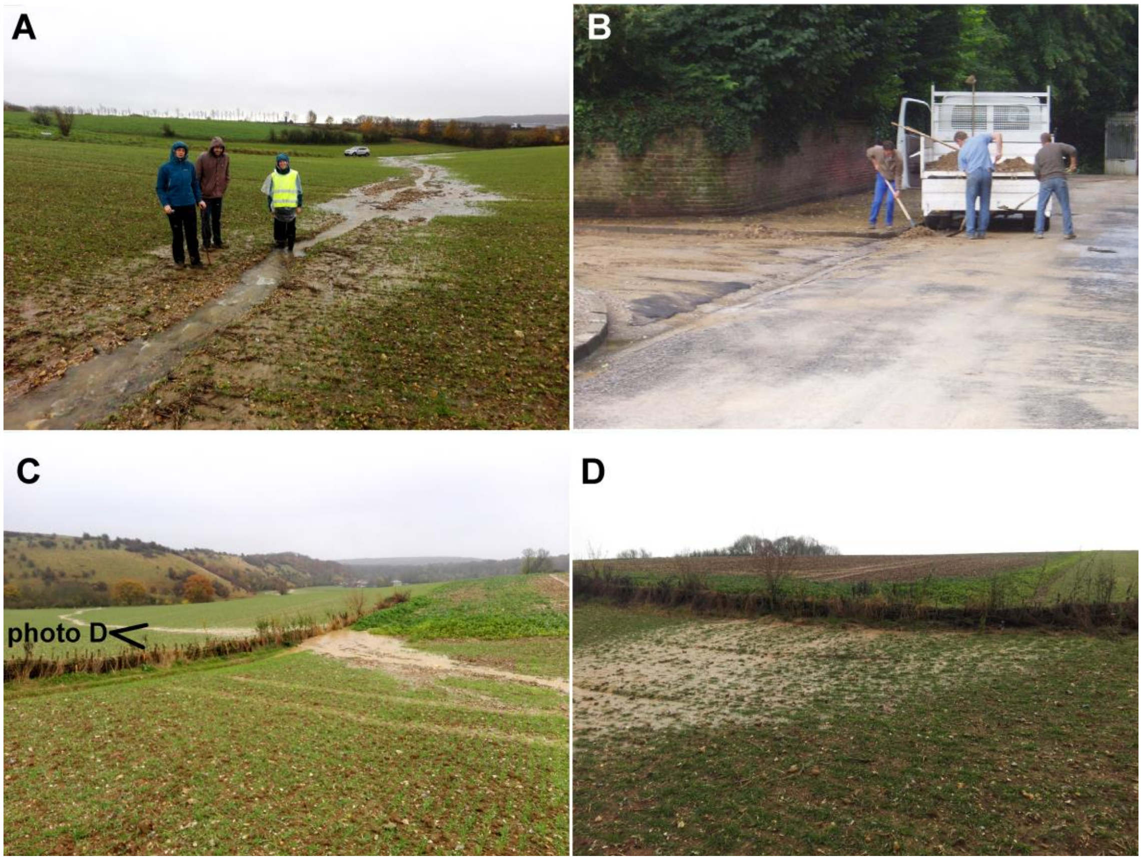

Figure 1: Open-field agricultural landscapes that are highly vulnerable to hydrogeomorphic hazards. (A) Ephemeral gully erosion, (B) Road cleaning subsequent to a mudflow hazard, (C) Fascine as control measure viewed from the top while buffering runoff and sediment, and (D) Viewed from downslope indicating the diffuse release of runoff and sediment. (photograph B by www.smageaa.fr).

Field observations and limited experimental studies provide some insight into the hydrogeomorphic effect of fascines. As biophysical buffers oriented perpendicular to the flow, the hydrological effect of fascines is to reduce flow velocities (by increasing the hydraulic roughness) up to a factor of three (Ouvry, 2012; Richet et al., 2016). This causes water to pond behind them, creating a backwater effect that encourages infiltration and sedimentation (Fig. 1C). Sediment trapping efficiencies of 16-99% are reported in literature, and consist especially of coarse particles (Ouvry, 2012; Degré et al., 2013; Bielders et al., 2016; Richet et al., 2016). Downslope of fascines, runoff (with fine suspended sediment) is released in a diffuse way (Fig. 1D), and concentrates again in the thalweg only a few metres below the vegetation barrier. No information, however, exists on the effect of fascines over longer periods (15 yr in this study) and how the fascines affect recurring ephemeral gullying along valley reaches. Various leaflets promoting land management, and flood and erosion control, suggest that fascines limit the development of ephemeral gullies.

In the Aa River basin, most important natural hazards are related to extreme hydrogeomorphic events such as mudflows and floods (www.prim.net). Mudflows cause significant damage to infrastructure and settlements and induce large costs, as illustrated by the 24 July 2008 event in Hallines (Fig. 1B). Floods also occur frequently on the Aa River floodplain, and its lower part has been recognized as a major regional risk zone. The perennial Aa River, with an average discharge of 5.7 $m^3 s^{-1}$ (at Wizernes), is vulnerable to winter floods when heavy rains occur. As soils lack crop cover in winter, they are also prone to surface sealing. Under these circumstances, a maximum peak discharge of 60 $m^3 s^{-1}$ was recorded in March 2002 (www.SmageAa.fr). Few studies of gully erosion exist in the Aa River valley. Auzet et al. (1993) were probably the first to study ephemeral gully erosion in the Aa River basin, indicating that the spatial variability of gully volume can be largely explained by crop cover and surface sealing. Hardy (2001) examined gullying in the Aa River basin between 1947 and 1995, and found that with 76% of the catchment soils sensitive to soil crusting, land consolidation to produce larger plots and the reduction of hedges caused the vulnerability to gully erosion to increase. The objective of this study is to investigate the success of recent land management efforts on ephemeral gully erosion dynamics. We focus on the effect of fascines and explore the connection between gully formation and precipitation amounts and magnitudes.

2. Materials and methods

2.1. Study area

The study area consists of the upper Aa River basin (643 km²) in the Nord-Pas-de-Calais region of northern France (Fig. 2). Altitudes range between sea level and 210 m (plateau of the Artois) and average slope gradients for croplands range from 2.3% to 5.3% (Table 1). Vulnerability to gullying is considered severe at slope gradients >3% (Hardy, 2001). Cropland covers 67% of the basin, mainly managed in open-field, mixed crop-livestock farming schemes with plot sizes that average 2.7 ha (Table 1, Hardy, 2001). Geologically, the upper Aa basin belongs to the Paris Basin, a tectonic basin which was filled by marine transgressions in Mesozoic times, and uplifted with the Alpine orogenesis. Pleistocene loess (reaching thicknesses of more than 10 m in places) or the underlying chalk-with-flint of Seno-Turonian age (Sommé, 1980; Desoignies and Thibaut, n.d.) is commonly exposed in the basin. Cenozoic sands and clays occur in limited extent and are often forested or found in wetlands. A narrow strip of Holocene alluvium can be found along the Aa River and its tributaries, which is mainly under pasture or urbanized and industrialized. Clay-loam and loamy soils dominate 76% of the catchment (Hardy, 2001), often with a clay-with-flint eluvial layer at the interface between the loess cover and the chalk (Nyssen et al., 2014). Because of Pleistocene periglacial processes (Gallois, 2009), the loess is in many places mixed with clay-with-flint, and this covers most of the catchment (Hardy, 2001). The most common soil types are

Brunisols, Rendosols, Calsosols, Calsisols, and Neoluvisols (Masson et al., 2000).

Table 1: Vulnerability ratio to gully erosion per crop type

Crop type	Land cover fraction (%)	Gullies (%)	Ratio	Average slope gradient (%)
Wheat	37.1	46.6	**1.26**	4.3
Grazing land (permanent)	25.5	5.1	0.20	
Maize	11.8	32.6	**2.75**	4.4
Barley	7.6	3.9	0.52	4.7
Other industrial cultures (sugar beet, mustard)	4.6	2.8	0.61	3.2
Vegetables (potatoes, onjons)	3.5	1.1	0.32	2.3
Rapeseed	3.4	2.8	0.84	4.8
Grazing land (temporary)	2.0	1.1	0.55	
Animal fodder	1.3	1.1	0.86	5.3
Other cereals (oat, spelt)	1.1	1.7	**1.54**	5.1
Fibre plants (flax, hemp)	1.1	0.6	0.52	3.9
Protein crops (beans, lupine, peas)	0.3	0.6	**1.62**	5.0
Other	0.6	0.0	0.00	n.a.

Intensive polycultures (cereals, sugar beets, potatoes) are common on the loess-covered hills. Land use changes are limited in the study area, with only a small reduction in cropland area (-5%) and an increase in urban area (+4%) over the period 1947-1995 (Hardy, 2001). More importantly, modernization in agriculture has caused land consolidation in land management schemes, which produced an increase in plot size and a reduction in hedge lengths (bocage landscape) (Hardy, 2001). These reforms caused soil erosion to increase in the Nord-Pas-de-Calais region, becoming one of the most erosion-vulnerable regions of France (Montier et al., 1998). Mudflows are frequent, and the region ranks in the top five in France in terms of the density of mudflows. Over the past two decades, numerous initiatives were undertaken to address these issues (Ouvry, 2012), including improving agrarian management to improve infiltration, reducing runoff and erosion, enhancing infiltration and runoff retention in urban areas, or flood control schemes in alluvial plains.

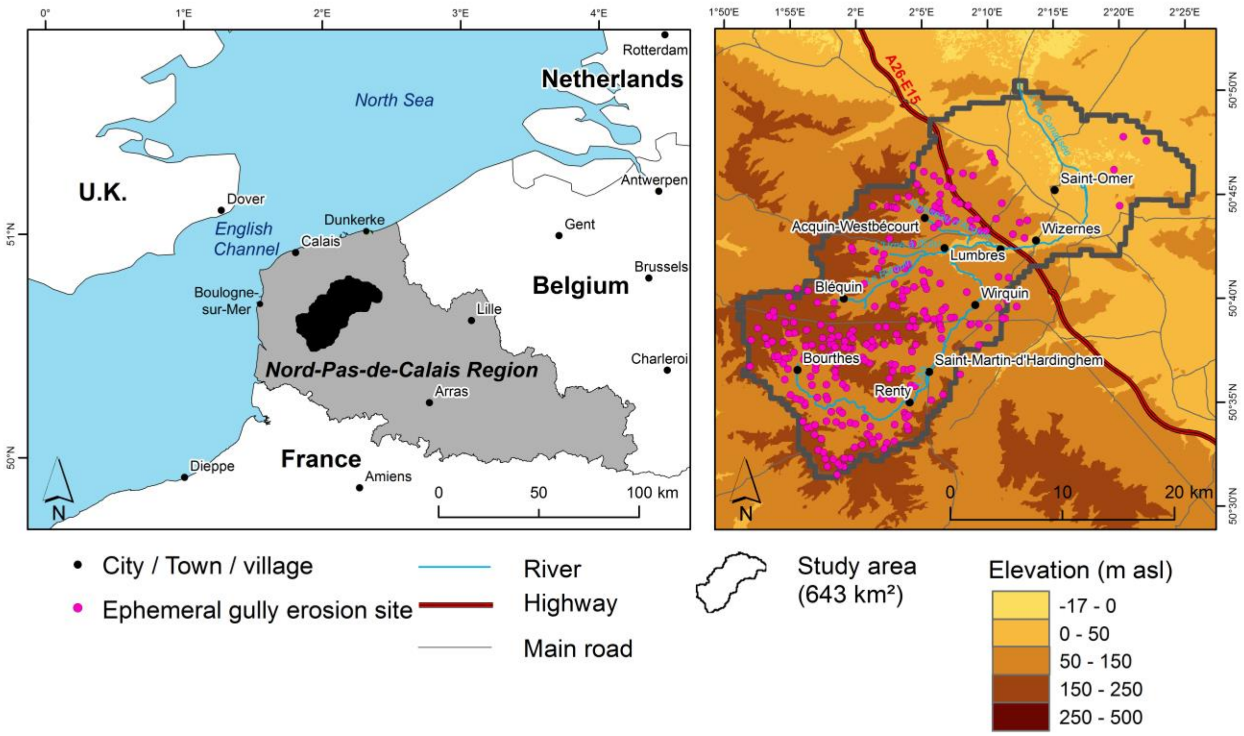

Figure 2: Study area in northern France, with detail (left) of the oro-hydrography of the Aa basin and (right) recurrent ephemeral gully erosion sites identified from a diachronic analysis of aerial photographs. (Elevation data from SRTM-data, www.cgiar-csi.org, administrative outlines, rivers and roads from www.data.gouv.fr).

2.2. Mapping gully length

As a proxy of the hydrogeomorphic response of the landscape, and mirroring the success of land management efforts in headwaters, ephemeral gully length (G_l, km) and gully density (G_d, m ha^{-1}) was studied over the period 1947-2012 using aerial photographs from 1947, 1995, 2000 (partial catchment coverage), 2005, 2009, and 2012. The gullies for 1947 and 1995 were mapped by Hardy (2001). For the 2000-2012 period, colour orthophotographs created by Institut Géographique National (I.G.N., France) were used. The planimetric accuracy of these colour orthophotographs was equal to three pixels or 0.6 m. We investigated changes in gully occurrence over the sub-periods 1947-1995, 1995-2000, 2000-2005, 2005-2009, and 2009-2012 using grid cells of 500 x 500 m² (Hardy, 2001). All aerial photographs were taken in the late spring (June), showing the initial growth phase of crops, and occasionally, recent ploughing activities. Winter wheat or other cereals (roughly 75% of the cropland is covered by cereals during winter) are dominant in the crop rotation cycle during winter. Sowing of winter crops occurs mainly between late August and February, but regular field visits and key interviews confirm that most of the land has already been prepared for winter by mid-September. Winter crops may alternate with spring crops in crop rotation schemes, and after mid-winter ploughing, typical spring crops are sugar beets, maize, and potatoes. The 'resetting' of the gully length to zero (gullies are eliminated by ploughing) thus mainly occurs between mid-August and mid-September, after which gullies that develop would remain as seasonal scars. The gully lengths reported in this paper thus reflect gullying that occurred approximately from 15 August to 15 June. The aerial photographs (scale of 1:25,000 for 1947, and 1:30,000 for 1995) and I.G.N. orthophotographs with pixel sizes of 0.2 m allowed ephemeral gullies to be easily mapped. Even though mapping the ephemeral gullies is to some extent subjective, we used as minimal criterion the incision of plough ridges by the gully.

2.3. Quantifying land and environmental controls

In order to investigate the effect of land management and environmental controls on ephemeral gully development, we analysed rainfall characteristics, crop cover, and the implementation of fascines in the Aa River basin between 1947 and 2012. These factors can be considered as the key controls of the occurrence of ephemeral gullies, given the soil-topographical conditions in the study area.

Cumulative precipitation (P_{cum}, mm) was obtained for the period 15 August to 15 June of 1946-1947, 1994-1995, 1999-2000, 2004-2005, 2008-2009 and 2011-2012. Since gullies mainly incise during the most intensive rainfall events, the 24-h maximum precipitation ($P_{\mathrm{24h.max}}$, mm) was also determined. Rainfall data was acquired from the nearby Méteo France weather stations of Boulogne-sur-Mer (50°43'54"N, 1°35'54"E) (for 1946-1947 data from the nearby Saint-Etienne-au-Mont was used), Dunkerque (51°03'18"N, 2°20'18"E), and Lille-Lesquin (50°34'12"N, 3°05'48"E). These stations are 30, 40, and 60 km, respectively, from the Aa River basin (Fig. 1).

Fascines and grass buffer strips were mapped from the orthophotographs, and could be easily observed at the scale of the aerial photographs. We evaluated gully development by identifying changes in the occurrence of these land management structures from 2005-2012 (because the first fascines were only applied since 2001) in the Aa River basin using 500 x 500 m² grid cells.

Crop cover was assessed by considering the main crop type present. The registration of the main crop type was based on the RPG data (French: *Registre Parcellaire Graphique;* Agence de Services et de Paiement), which is a GIS-based database on the main crop type grown per cluster of parcels of each farm (French: *îlot*). The lack of data limited our analysis of crop cover to the year 2012, which we assume is representative of the entire study period. In total, the RPG data covers 62% of the land surface. We analysed the relationship between the main crop type and gully occurrence per farm. To verify possible bias caused by the interrelation between crop rotation and slope gradient, we also investigated the effect of the average slope gradient on the main crop type.

In addition to the effect of dominant crop type, winter cover crops can also play a role in

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limiting erosion because these crops improve infiltration, reduce overland flow, and limit the formation of soil crusts. Data on winter cover crops were, however, not readily available. Desmyttere (2004) estimated that only 73-78 km² (~16-17%) of cropland in the Aa River basin had the potential to support winter cover crops because these crops are not possible when crops like winter wheat are being grown, or when sugar beets or maize are grown during spring-summer (they are harvested late, in October-November).

Since 2014, winter cover cropping is mandatory according to national and regional legislation, and before, several programs were in place that had a more limited impact (SmageAa, FEADER). By late December, 78% of the winter cover crops are harvested (Desmyttere, 2004). Because winter cover crops only became relevant over the past years, their effect was not considered explicitly.

2.4. Sediment storage behind fascines

In order to improve our understanding of the effect of fascines on sediment dynamics and gully development, the previous analysis was expanded by a fieldwork-based case study. Hence, we focussed on a subarea (27.5 km^2) of the Aa River basin with a high G_d. Between November 2015 and May 2016, the sediment storage by fascines was quantified. Sediment storage was calculated by multiplying the volume of the sediment cones (surface area x average depth determined by augering) with the bulk density (using one 100 cm² Kopecky ring sample per site; weighted after oven-drying). Sediment storage behind fascines was compared to a quality assessment of the fascines, based on a semi-quantitative assessment of the condition of the posts or poles, the condition of vegetative filters (willow bunches mainly), the ground contact, presence of gaps in the structure, and the positioning of the fascine relative to the thalweg.

We performed a detailed field survey on the effect of fascines on ephemeral gullying for the multiple rainstorm event of 17-18 November 2016 with 53.2 mm of precipitation in two days. The gullies and their headcut locations were mapped in detail in the field, and the topographic threshold for gully head development was defined following the guidelines of Torri and Poesen (2014) and Monsieurs et al. (2015). This involved using a fixed coefficient of $b = 0.38$ while fitting the data to the power function $S = kA^{-b}$ (where S = slope and A = catchment area). The threshold was defined by using the lower limit of the 95% prediction confidence interval around the mean (Vandekerckhove et al., 1998). Investigating the precise impact of fascines on gully morphology was completed for a well maintained fascine (that represents a best-case scenario) implemented centrally along an ephemeral gully in Quelmes. Gully cross sections were measured at regular intervals from the head to the end using Structure-from-Motion Multi-View Stereo (SfM-MVS) methods. This involved recording the sections using multiple photographs and processing them in PhotoScan (Agisoft) (Frankl et al., 2015). Event-based storage behind the fascine was also quantified using SfM-MVS.

3. Results

3.1. Controls on spatial and temporal variations of ephemeral gullying

In total, we identified 269 sites vulnerable to ephemeral gully erosion, i.e., sites that were impacted by erosion at some time in the past 70 yr (Fig. 2). The total length of ephemeral gullies, G_l, varied between 24.9 (2012) and 84.4 km (1995) (Table 2). Gully density G_d varied between 0.39 m ha^{-1} (2012) and 1.31 m ha^{-1} (1995) (Table 3). These values are slightly higher when only considering cropland (given that other land uses are not prone to ephemeral gullying in the Aa River basin). Spatial variability of G_d is, however, considerable (reflected by the large standard deviations for the mean G_d, Table 3). At the scale of municipalities, a maximum G_d on cropland of 15.67 m ha^{-1} was registered in 1995 (Table 3).

Table 2: Relationships between gully length, precipitation and fascines in the Aa basin

	1947	1995	2005	2009	2012	Pearson r^2 between G_l and P_cum ($P_{24.\mathrm{max}}$)
G_l (km)	47.8	84.4	37.6	31.7	24.9	R^2=
P_cum (mm) Boulogne-sur-Mer ($P_{24.\mathrm{max}}$)	614 (26)	725 (32)	539 (44)	552 (27)	519 (26)	*0.97* (0.01)*
# fascines (on % of gully erosion sites)	0 (0)	0(0)	227 (22)	267 (28)	272 (29)	

* Significant with p = 0.03

Cumulative precipitation (P_cum) from the Boulogne-sur-Mer station displayed a strong significant relationship with G_l (R^2 of 0.97), making it the most relevant rainfall variable considered (Table 2). Unexpectedly, $P_{24\mathrm{h.max}}$ was not significant as an explanatory variable. Because the meteorological station is far away, it may not have captured the specific high-magnitude events that caused gullying in the study area, an observation also discussed by Boardman (2015). Fascine implementation has grown substantially since 2001, rapidly increasing to 227 in 2005 and 272 in 2012, representing 22% and 29% of the gully erosion sites, respectively (Table 2).

Table 3: Gully density G_d (m ha^{-1}) variability at the scale of the entire Aa River basin and the municipalities. Descriptions for cropland are reported separately since ephemeral gullying does not apply to other land uses.

		1947		**1995**		**2000***	
		all land uses	cropland	all land uses	cropland	all land uses	cropland
Aa River basin		0.74	1.11	1.31	1.96	0.58	0.87
Municipalities	Mean	0.83	1.08	1.48	1.87	0.64	0.91
	s.d.	1.40	1.62	2.07	2.62	1.31	1.90
	Max	7.96	8.07	9.35	15.67	6.42	10.75

		2005		**2009**		**2012**		**Long-term average**	
		all land uses	cropland	all land uses	cropland	all land uses	cropland	all land uses	cropland
Aa River basin		0.54	0.81	0.49	0.74	0.39	0.58	0.68	1.01
Municip ali-ties	Mean	0.60	0.88	0.52	0.64	0.43	0.56		
	s.d.	0.89	1.37	0.70	0.73	0.63	0.78		
	Max	3.52	5.68	3.05	2.49	2.57	2.92		

Table 4: Net increase or decrease in mean gully length for erosion sites (N=269) as explained by fascines

	1995-2005			2005-2009			2009-2012	
Fascine	**N**	**ΔG_l (m)**		**N**	**ΔG_l (m)**		**N**	**ΔG_l (m)**
With	60	-234	-85%	75	-28	-25%	77	-29
Without	209	-157	-36%	194	-17	-8%	192	-19
Sign. (two-tailed t-test)		*0.217*			*0.704*			*0.69*
Newly established	60	-234	-85%	16	-70	-31%	6	-73
Removed	0	n.a.	n.a.	1	0	0%	4	-42
Present	0	n.a.	n.a.	59	-16	-3%	71	-26
Not-Present	209	-157	-36%	193	-17	15%	188	-19
One-Way ANOVA		*0.217*			*0.481*			*0.944*

Spatio-temporal gully development shows a large degree of heterogeneity in the catchment for all periods, and only a limited number of sites show recurrent gullying across all time periods or since the first implementation of fascines (Fig. 3). The most vulnerable zones to erosion occur in the southeastern part of the catchment and the area to the north of the 'ruisseau d'Acquin' stream. Over all periods gully occurrence varied substantially. While an increase in ephemeral gullies occurred between 1947 and 1995, the opposite trend was observed from 1995 to 2005, mainly attributed to the 1995-2000 period (Fig. 4). Since 2005, the proportion of the study area exhibiting gully occurrences is rather constant, although spatial variability remains high.

Figure 4: Summary of gully occurrences (from Fig. 3). Since 2005, variability in ephemeral gully absence - presence combinations remain rather constant. * based on partial area coverage (see Fig. 3).

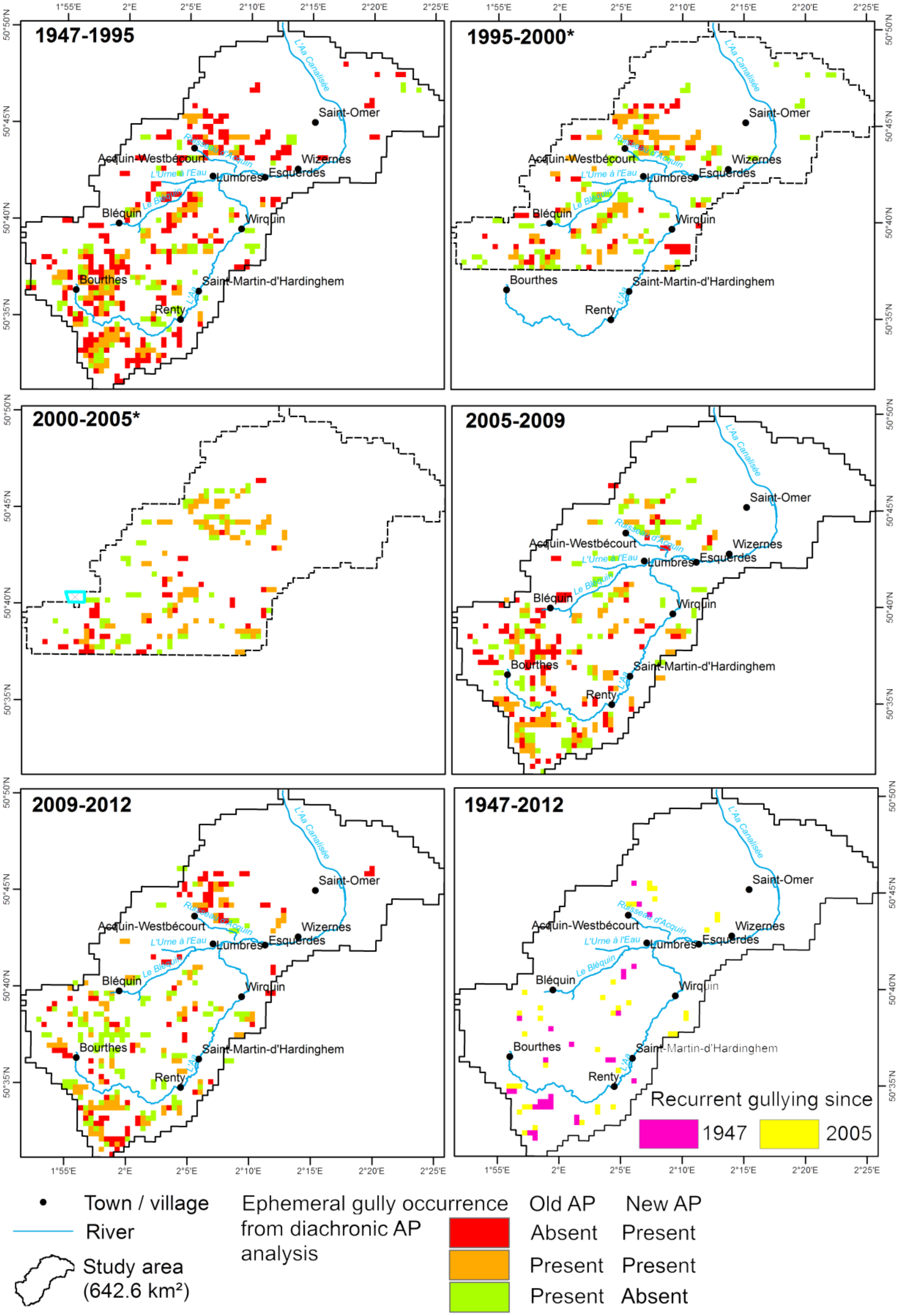
1947-1995
1995-2000*
2000-2005*
2005-2009
2009-2012
1947-2012
Saint-Omer
Acquin-Westbécourt
Wizernes
Lumbres
Esquerdes
Bléquin
Wirquin
Bourthes
Saint-Martin-d'Hardinghem
Renty
L'Aa Canalisée
Ruisseau d'Acquin
L'Urne à l'Eau
Le Bléquin
L'Aa
1°55'E
2°E
2°5'E
2°10'E
2°15'E
2°20'E
2°25'E
50°50'N
50°45'N
50°40'N
50°35'N
Recurrent gullying since
1947
2005
Town / village
River
Study area (642.6 km²)
Ephemeral gully occurrence from diachronic AP analysis
Old AP
New AP
Absent
Present
Present
Present
Present
Absent

Figure 3: Spatio-temporal gully absence and presence analysed at the scale of 500 x 500 m grid cells over 1947-2012. By comparing per period observations from the Old Aerial Photograph (AP) to the New one, the combination of gully "Absence – Presence" points to gullies that only occurred in the New period, while "Presence – Presence" points to reoccurring gullying. "Presence – Absence" indicates that ephemeral gullying could only be attributed to the Old situation.

For the periods 1995-2005, 2005-2009 and 2009-2012 we investigated whether the presence of fascines caused gully lengths to decrease per site (the observation year 2000 was not considered here since it only covers the catchment partially). Net gully length decreased for all periods, but the decrease in gully length was more marked for the sites with fascines (Table 4). This, however, only considers the presence of fascines; not considering when they were implemented is a potential bias in our interpretation. Therefore, we identified whether gully length change varied when considering fascines that were newly established, removed, present, or not present for the periods 1995-2005, 2005-2009 and 2009-2012. The decrease in gully length was on average most marked for the newly established fascines, with a 31-85% decrease in gully length (Table 4). Due to high variability, however, these effects were not statistically significant.

To determine the effect of crop type on gullying, a ratio was computed to express relative degrees of vulnerability (Table 1). A ratio of 1 indicates that the fraction of gullies attributed to a certain crop type is proportional to the land area of that crop. A ratio greater than 1 coincides with an increased vulnerability to gully erosion. Maize was found to have the highest ratio (2.75), followed by protein crops and cereals (including wheat). The Aa basin is dominated by wheat crops, which are at an early stage of growth stage in winter, rendering the soil prone to surface sealing. In contrast, maize is sown in the early spring, thus leaving the land unprotected to early season thunderstorms.

3.2. Case study on recent hydrogeomorphic dynamics in headwaters

Fifty-nine percent of the fascines visited during the winter of 2015-16 (29 total) functioned as a sediment sinks. Given measurement precision (0.1 m^3), the fraction of buffering fascines can be conservatively reduced to 47%. In terms of trapping efficiency, 55% of fascines were considered to be good sediment buffers, while 31% were determined to be moderate and 14% poor. In total, 21.4 m^3 of sediment was stored during the monitoring period, which given an average bulk density of 1.13 Mg m^{-3}, coincides with 24.2 Mg or 0.009 Mg ha^{-1}. On average, every fascine stored 1.7 Mg of sediment, with a maximum of 3.7 Mg during the winter period (Fig. 5).

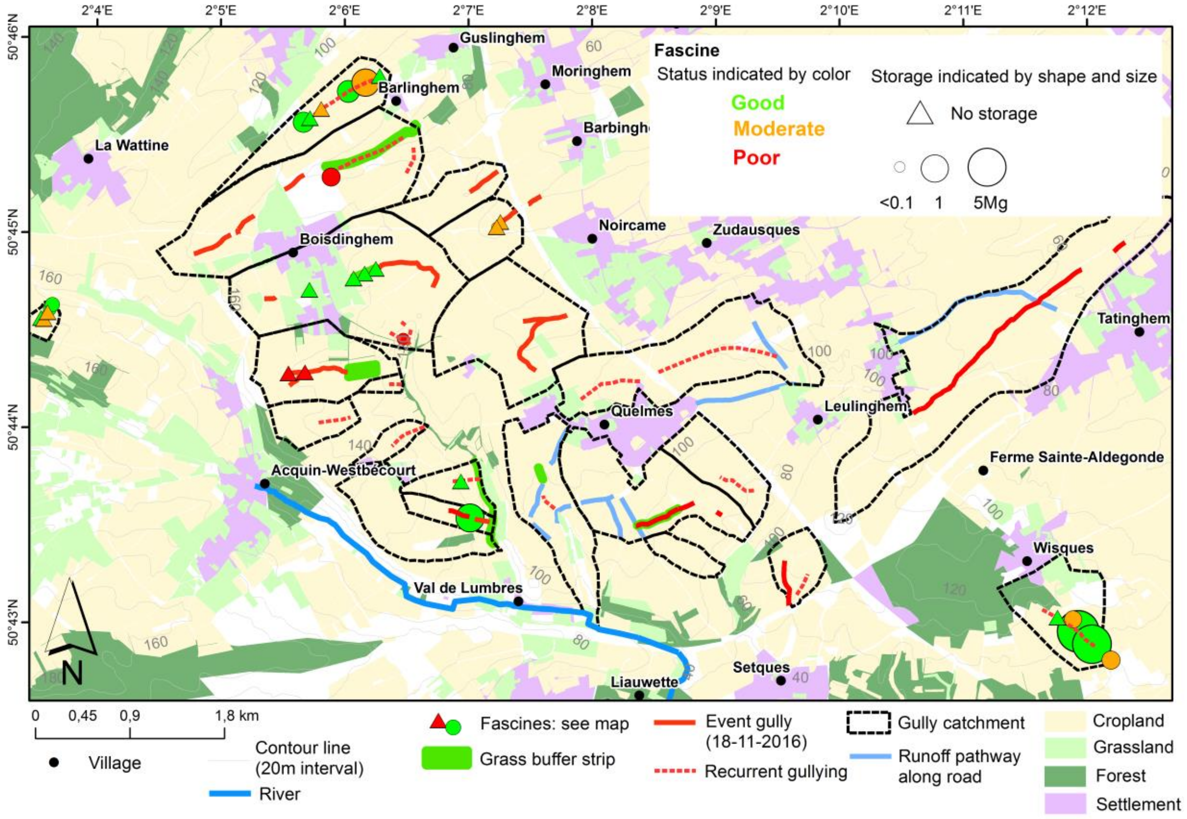

Figure 5: Sediment storage by fascines in the case study following the winter of 2015-2016 and gully erosion dynamics following a recent thunderstorm of 18 November 2016. (Elevation data from SRTM-data, www.cgiar-csi.org, administrative outlines, rivers and roads from www.data.gouv.fr).

Detailed field visits following the rainstorms of 17-18 November 2016 indicated that the agricultural land remains very sensitive to hydrogeomorphic change. Approximately half of the catchments with recurrent gullying (10 of 19) were impacted during the rainstorm events, yielding a total G_l of 3.7 km (Fig. 5). The corresponding topographic threshold line is shown in Fig. 6. Given that no recent change in the cropland vulnerability was found (see section 3.1), adding the

S-*A* data for all the recent recurrent headcuts increased the robustness of the threshold equation - the average *k*-value was 0.11±0.06, with a fixed *b* exponent of 0.38.

Considering the influence of land cover, gully development was minimal in locations where winter cover crops did mature and achieve dense ground cover by mid-November. Elsewhere, however, partially successful germination left bare spots in the arable land vulnerable to runoff and erosion. In particular, runoff was concentrated along wheel tracks in bare fields that had been recently harvested. In a similar vein, road networks led to rapid runoff in thalwegs (Fig. 5). Locations with compacted soils (e.g., sugar beet fields) and surface sealing (e.g., winter wheat fields) were major contributors to runoff.

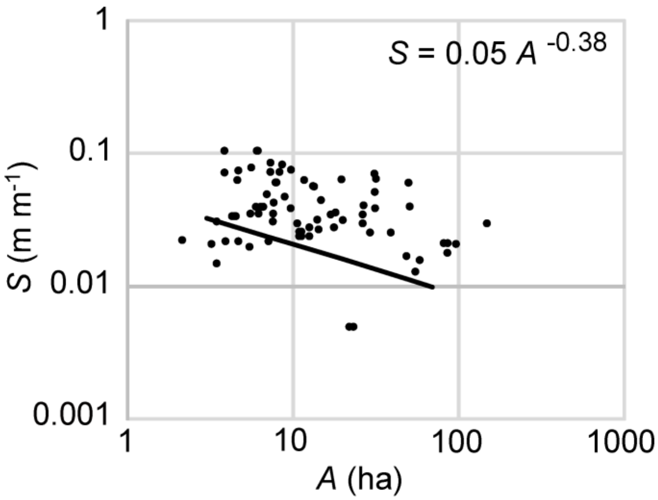

Figure 6: Topographic threshold for gully heads in the case study area (Fig. 5).

Overall, fascines were moderately effective at storing sediment released from upslope croplands. Effectiveness seems to have been limited by poor maintenance (missing willow cuttings at the soil surface, large gaps, rotten poles, etc.), as well as fascine design (that do not extend far enough from the gullies). For example, some gullies simply migrated around the outside of the fascine (see Fig. 7A). However, in situations where fascines were well maintained and designed they proved quite effective at both storing an impressive amount of sediment (Fig. 7B) and, in certain instances, completely ending sediment transport via gully networks. Single-event storage at the fascine of Fig. 7B was 12.5 Mg. However, even though their hydrological buffering effect was apparent, runoff concentration below fascines often resulted in a new incision (Fig. 7B) that we interpret to be a clear water effect (Boix-Fayos et al., 2007) given the drop in sediment concentration as compared to the more limited reduction in peak discharge. Although the fascine may not be able to eliminate gullies, the modified discharge characteristics affect cross-sectional properties. From our case study in Quelmes, the average cross section below the fascine was significantly smaller than above the fascine (t-test, p=0.015) as determined by quantifying gully cross sections in detail (e.g., the example of Fig. 7B, Fig. 8)

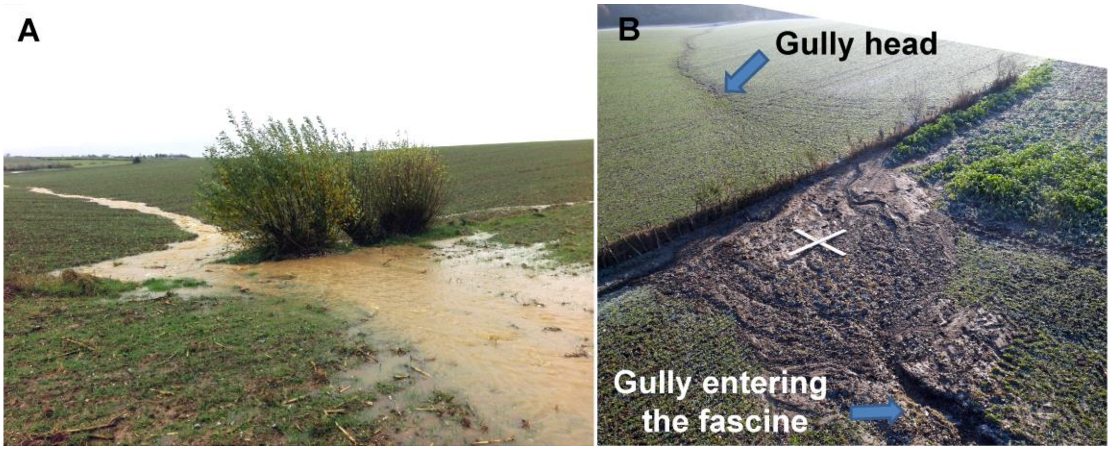

Figure 7: (A) Poorly maintained fascine unable to store sediment due to bypassing and, (B) well-implemented recent fascine that stores a large volume of sediment following a single rainstorm.

Note that below the fascine a new gully initiated due to a clear water effect, though of lesser magnitude.

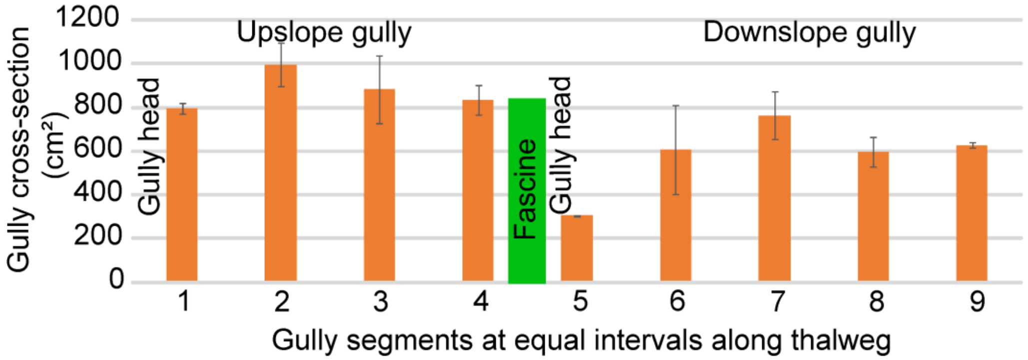

Figure 8: Gully cross-sectional change as impacted by a fascine.

4. Discussion

4.1 The magnitude of ephemeral gully erosion in Northern France

Ephemeral gully erosion densities reported in this study are very low as compared to values reported by other studies (Table 5). This can largely be explained, however, by the scale of investigation. Few other studies report ephemeral gully densities at the scale of an entire river basin. The size of our study area is one order of magnitude larger than the second largest study area for which data on ephemeral gully erosion densities were reported (Table 5). As G_d decreases with an increase in study area (Fig. 9), care must be used in comparing our results to those of other studies. Studies that consider areas smaller than 1 km² target areas that are especially vulnerable to ephemeral gully erosion and do not necessarily represent their wider region. Furthermore, because the temporal variability in G_d is high (Table 3), investigating gully erosion over a short period may reflect extreme events (Øygarden, 2003). Our results should, therefore, mainly be considered at the spatial scale of municipalities (2-23 km²) and compared to other long-term studies. Plotting the five most erosion-vulnerable municipalities in Fig. 9 indeed indicates that G_d values reported in this study (2.23-4.30 m ha^{-1}) are comparable to other study areas of similar sizes.

Table 5: Variability in ephemeral gully erosion density (G_d, m ha^{-1})

Location	Study area (km²)	G_d (all land uses)	G_d (cropland)	Study period	Reference
Belgium, central	28.24 (cropland)	x	5.97	Multiple years (1947-1996)	Nachtergaele and Poesen (1999)
Belgium, central	5.5	2.54	x	Multiple years (1963-1986)	Vandaele et al. (1997)
China, Heilongjiang	0.64 (cropland)	x	6.64	≤ 1 year (2005)	Zhang et al. (2007)
China, Inner Mongolia	0.55 (29% cropland)	19.55	36.96	≤ 1 year (2002-2003)	Cheng et al. (2006)
China, Shaanxi, loess plateau	0.45	192.94	x	1 year 2002	Cheng et al. (2007)
Czech, central Bohemian region	0.34 (cropland)	x	15.45	Multiple years (1953-2013)	Báčová and Krása (2016)
France, north	634 (67% cropland)	0.68	1.04	Multiple years (1947-2012)	This study
Italy, Umbria	48 (60% cropland)	2.92	4.84	≤ 1 year (March-May 2010)	Fiorucci et al. (2015)
Italy, Sicily	1.35	1.5	x	Multiple years (1996-2013)	Capra and Spada (2015)
Italy, Sicily	45	0.12	x	≤ 1 year (2014)	Ollobarren et al. (2016)
Norway, south	0.71 (cropland)	x	118.77	≤ 1 year (1990)	Øygarden (2003)
Portugal, Alentejo	40	9.35	x	3 years (1970-1985)	Vandaele et al. (1997)
Spain, northwest	0.37 (cropland)	x	12.91	2 years (1997–1999)	Valcárcel et al. (2003)
Spain, Navarra	0.88	8.40	x	1 year (1995-1996)	Casalí et al. (1999)

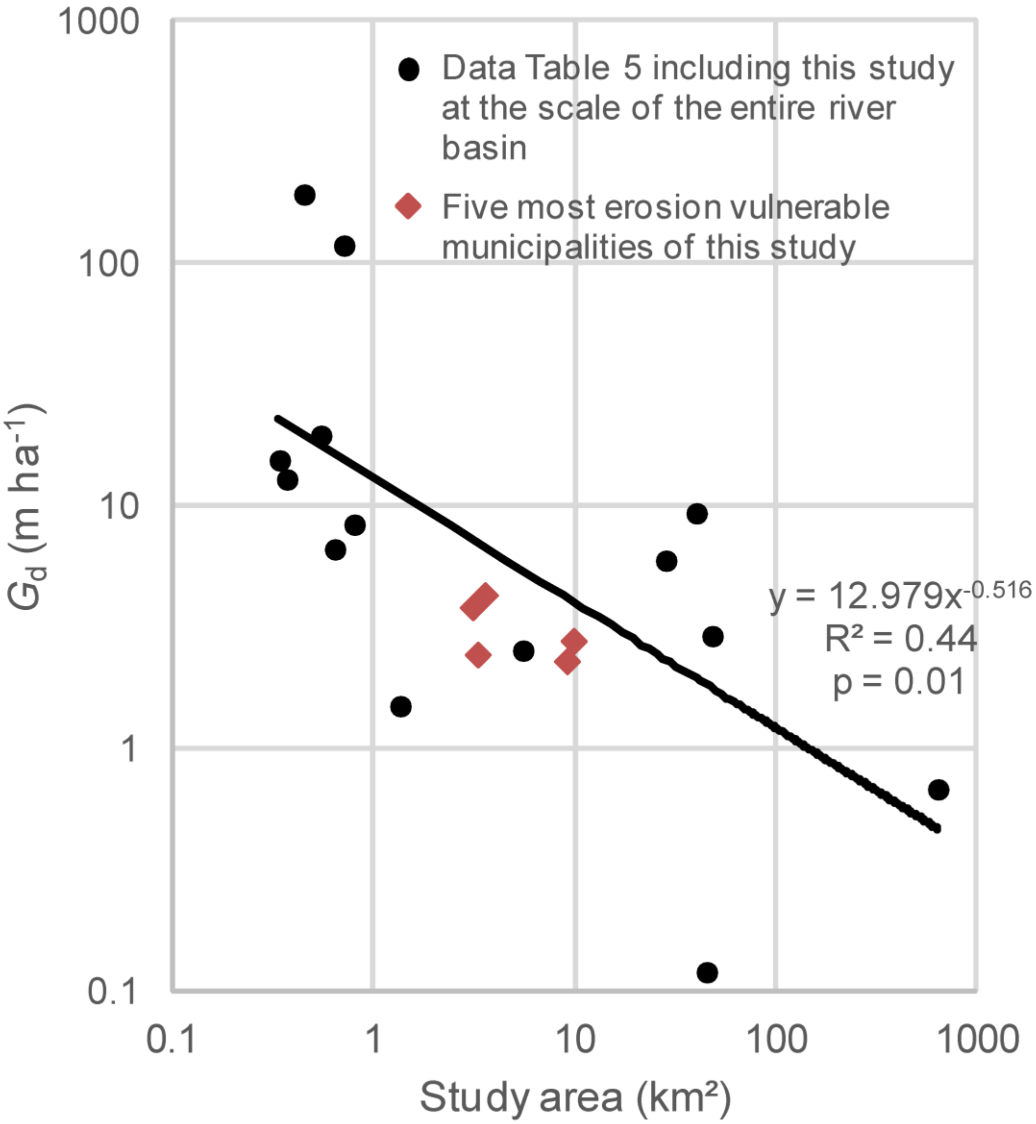

Figure 9: Relationship between the size of study areas and gully densities G_d reported in the literature.

4.2. The implementation of fascines as erosion control measure

The implementation of fascines as a measure to stabilize slopes and protect against erosion has a long tradition (Lachat, 1991; Evette et al., 2009; Stokes et al., 2009) and has been utilized across many regions, especially as riverbank or mountain torrent stabilization measures (Rey, 2004; Patel, 2012). Because of increasing labor costs over time, however, bioengineering methods have mostly been replaced by hard engineering approaches such as retention ponds (Boardman et al., 1994). Their current implementation can be viewed as a rediscovery and improvement of past bioengineering methods. Fascines are often implemented in a land management strategy that also aims at improving the ecological connectivity of the landscape (Devkota et al., 2006; Li and Zhang, 2006) as well as improving aesthetics.

Given the promising results of pilot projects in the municipalities of Aquin-Westbécourt, Moringhem, and Thiembronne, the moderate cost of ~20-35 euro per metre and experiments such as those by AREAS (*Association de recherche sur le Ruissellement, l'Erosion et l'Aménagement du Sol*; reviewed in Richet et al., 2016), fascines were widely implemented in the Aa River basin. Planning and implementation of fascines was accomplished in a thoughtful manner according to design guidelines. For example, fascines were centrally located in the thalweg and were constructed wide enough to allow buffer flows (Fig. 1 C, D). In addition to practical considerations (e.g., plot boundaries), topographic threshold lines as shown in Fig. 6 can be used to optimally identify catchments along thalwegs where recurrent gullying is expected to occur in croplands. However, while farmers initially benefited from decreased soil erosion at no cost to them, they did have to bear the cost of on-going maintenance as specified by the program. Farmers also often see fascines as temporary measures (following severe hydrogeomorphic events) and, thus, do not know how to maintain them in the long term (Heitz et al., 2012). Where willow stakes do not survive (often due to the interaction with farming activities), they need replacement. In a similar manner, bundled willow branch cuttings will also eventually decompose and need to be replaced. Previous work has indicated that the effectiveness of fascines relates to their age and that without proper management fascines only have a life expectancy of four years (Degré et al., 2015; Bielders et al., 2016). Others report survival rates as low as 54% for willow stakes after only 1.5 yr following implementation (Flessner, 1997). Moreover, in order to sustain the runoff buffering capacity, excess sedimentation needs to be removed at least once a year as well as following major runoff events. Without regular maintenance fascines will typically lose their buffering capacity and will need replacement after only a few years. Because farmers are usually not concerned with mudflows resulting from ephemeral gullying in their fields, and given that water ponding behind fascines disrupts their farming activities, they may not necessarily appreciate the positive effect of fascines. Our work indicates, however, that their impact is not trivial. Sediment storage by fascines reported here is similar to the amount of material that was recently quantified in Wallonia (Belgium), where six fascines stored 0.5-1.7 Mg over a half year period in 2015 (compared to an average of 1.7 Mg stored by the fascines in this study). Seventy percent of the fascines from that study were in good condition and were well designed, whereas 55% of the fascines described here (implemented since 2001) are functioning as good sedimentation buffers. For the entire Aa catchment, these figures drop even further to 23% (according to the a recent SmageAa study). This also indicates the impact of time on fascine quality and the need to invest in maintenance.

5. Conclusions

The Aa River basin of northern France, similar to many other loess-covered regions, displays open-field agricultural landscapes where ephemeral gullies are common. Here we observed that despite efforts taken to mitigate erosion, gullying remains a major challenge. Over the entire basin, densities of 0.58-1.96 m ha^{-1} can be expected in cropland during the winter half-year with year-to-year variability largely explained by winter precipitation. The spatial variability at the scale of municipalities, however, is high as demonstrated by a maximum G_d of 15.67 m ha^{-1} in 1995. Considering the five most erosion vulnerable municipalities of this study, long-term average gully densities (2.23-4.30 m ha^{-1}) are comparable to those of other studies of similar spatial extend. Fascines have been implemented since 2001 in the study area and are present on ~30% of the 269 gully erosion sites. We demonstrated that fascines have a positive effect on increasing the landscape's resilience to ephemeral gully erosion. Fascines tend to reduce gully lengths, especially when newly implemented (reduction of 31-85%). The gully length reduction is, however, quite variable and therefore not statistically significant. This is mainly due to the poor maintenance of fascines, as they are often bypassed by runoff flows. Furthermore, re-incision occurs downslope of fascines as a result of a clear water effect. Those re-incisions are smaller than the upslope gullies owing to the buffering of peak flows. For a given gully length, the total eroded volume is thus smaller. Fascines do store sediment because they function as buffers to runoff and sediment filters. An assessment over the 2015-2016 winter period for 29 fascines indicated that they store on average 1.7 Mg of sediment. A maximum storage of 12.5 Mg for only one fascine during a single rainfall event in November 2016 was observed, indicating significant potential as control measures when well implemented. This study demonstrates that vegetation control measures can reduce ephemeral gully erosion, but that improving their management in the appropriate socio-economic context is crucial.

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