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Characteristics and controlling factors of old gullies under forest in a temperate humid climate: a case study from the Meerdaal Forest (Central Belgium)

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Abstract

In many forests of Northwestern Europe old gullies can be found, but few studies have reported their genesis and characteristics. This study investigates these old gullies under forest in the large case-study area of Meerdaal Forest, in the Central Belgian loess belt. The objectives are (1) to determine the spatial distribution of these gullies, (2) to measure their morphological and topographical characteristics and (3) to reconstruct the factors that led to their development. In the 1329-ha study area, 252 channel-like incisions were mapped. Different types of incisions could be distinguished. Besides small and large gullies, many incisions were sunken lanes or road gullies. These road gullies are aligned along north–south oriented lines, whereas the concentration of old gullies is strongly related to the distribution of archaeological sites. Out of the 252 mapped incisions, 43 large gullies and 21 representative road gullies were selected for detailed morphological and topographical measurements. The characteristics of these two types of incisions were compared with ephemeral gullies formed under nearby cropland. Significant differences in morphology between the three types could be demonstrated. Ephemeral gullies under cropland and large gullies under forest differ significantly in all measured parameters, except bottom width. Both the old gullies and road gullies under forest have a significantly larger cross section and total eroded volume compared with the ephemeral gullies observed under cropland. This indicates that once formed, the old gullies were not ploughed in nor were they filled by sediment originating in their drainage areas, because of limited sediment production. Comparing topographical characteristics (i.e. slope at the gully head and runoff contributing area) of forest gullies and ephemeral gullies that formed under cropland yields important indications about their formation. The larger sedimentation slope of forest gullies, compared with ephemeral gullies and road gullies, suggests that the forest gullies incised on vegetated slopes as a consequence of runoff from the adjacent plateau, where the forest cover was disturbed. For the old gullies under forest, no relation between slope at the gully head and runoff contributing area is observed, probably because most gullies occur on very steep slopes. When simulating arable land-use in the study area, zones where ephemeral gullies are expected to develop can be predicted using published topographical threshold relationships. Comparing the zones where ephemeral gullies are predicted with the position of old gullies under forest leads to the conclusion that gully incision was most probably not triggered by extreme rainfall events

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and that they are not of periglacial origin. The observed gully pattern can best be explained by local, anthropogenically determined land-use changes.

Keywords: Gully erosion under forest; Central Belgium; Topographical thresholds; Human-induced land-use changes

1. Introduction

The problem of gully erosion in the West European loess area is well known and documented (e.g. Poesen and Govers, 1990; Papy and Douyer, 1991; Auzet et al., 1995; Ludwig et al., 1995; Nachtergaele et al., 2002). Most studies, however, focus on ephemeral gully development under cropland. With respect to permanent gullies, as observed under forest in the Belgian loess belt, relatively few studies have been conducted (e.g. Arnould-De Bontridder and Paulis, 1966; Langohr and Sanders, 1985; Gullentops, 1992; Poesen et al., 2000, 2003). Currently, little is known about their spatial distribution, about their morphological and topographical characteristics or about their genesis (Poesen et al., 2003). With the current climatic conditions in Northwestern Europe, no gully erosion is expected to occur under undisturbed forest vegetation, mainly because of the high infiltration capacity of these forest soils, which makes Hortonian runoff almost impossible. Therefore, these forest gullies must be old landscape features. Different hypotheses can explain the formation of these gullies. A first is that these gullies developed under forest as a consequence of high magnitude–low frequency rainfall events during which significant runoff was generated, even under a protective forest cover. Comparable with this is the hypothesis of Gullentops (1992), who, based on the study of peat sequences, stated that many large gullies formed under forest during the wetter Atlanticum (7800–5000 BP), a period characterised by higher rainfall intensities then today. A second hypothesis is that runoff was generated locally in areas with a disturbed forest cover due to human-induced land-use changes (e.g. cropland, intensive cattle grazing in forests, forest logging), and that reforestation occurred afterwards. A third hypothesis is a combination of human-induced land-use change and extreme rainfall. Bork et al. (1998) showed that this mechanism was the driving factor for the incision of many gullies presently under forest in Germany. A final hypothesis was proposed by Langohr and Sanders (1985) on the basis of research in the Zonien forest (Central Belgium), who suggested these old gullies could be periglacial features, cut into the loess cover long before a protective plant cover was established during the Holocene.

In order to elucidate the conditions leading to the development of gullies presently found under forest, representative old gullies in forested areas are studied in detail. More specifically, the objectives of this study are (1) to determine the spatial distribution of these old gullies under forest in a representative large study area, (2) to measure morphological and topographical characteristics of old gullies under forest and to compare them with the characteristics of ephemeral gullies formed under cropland and (3) to reconstruct the environmental conditions that triggered gully formation in a large forest area. Therefore, gully position is predicted based on the assumption that the entire area was used as cropland in the past. The predicted ephemeral gully pattern is compared with the distribution pattern of the mapped old gullies. Together with the distribution pattern and characteristics, these elements should indicate whether gully formation was triggered by extreme rainfall events, human-induced land-use changes, periglacial processes, or a combination of processes.

2. Study area

The focus of this study is on the Belgian loess belt and the area selected for this research is one of the last original forests in Central Belgium: i.e. the Meerdaal Forest (Fig. 1). As far as is known by historians, this forest was never deforested or used for intensive agriculture on a large scale.

The Meerdaal Forest covers almost 1700 ha. Part of the forest was inaccessible because of military

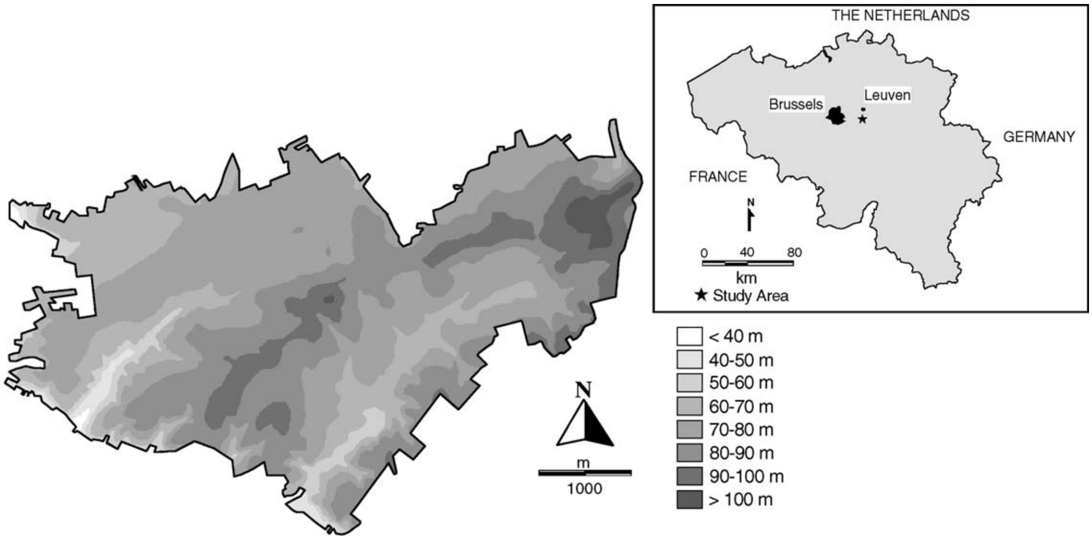

Fig. 1. Location of the Meerdaal Forest within Belgium and digital elevation model of the study area.

installations, therefore the study area is somewhat smaller (i.e. 1329 hectares). Altitudes range between 35 and 103 m a.s.l., with a typical rolling topography characteristic of the Belgian loess belt. However, steep slopes, even >25% do occur. Mean annual rainfall is ∼ 800 mm (Baeyens et al., 1957). The main soil types are Luvisols and Albeluvisols. Only locally, on eroded hilltops, Tertiary sands that underlie the loess deposits outcrop and there Podzols can be found (Baeyens et al., 1957).

3. Materials and methods

After conducting an intensive field survey to locate all channel-like incisions in the study area, their position was mapped with GPS (Trimble Pro-XL). Channel-like incisions were defined as linear incisions with a minimum length of about 15 m and a minimum depth of 0.2 m. Furrows and drainage ditches were excluded.

Mainly because of multi-path effects, large errors remained (maximum error up to several tens of metres), even after differential correction. Where possible, these errors were corrected manually. In total, 252 channel-like incisions were mapped. Three different types of incisions were recognised: small gullies (< 0.3 m depth, $n = 39$), large gullies (>0.3 m deep, $n = 43$) and road gullies ($n = 170$). The distinction between large gullies and road gullies will be discussed in detail later. A group of anthropogenic features was also mapped. These are structures that are clearly man-made. Some are large levees up to 3 m in height, but most of these structures are deep "sunken lane"-like features (maximum depth around 5 m), extending over several hundreds of metres, even on flat terrain. Although their original function is not fully understood, it is generally assumed that these features served as roads (Dens, 1908; Vincent, 1925; Martens, 1981).

In a second phase, the 43 large gullies and 21 randomly selected road gullies were characterised in more detail. The 39 small gullies were omitted from further detailed analysis, because they are not clearly visible in the landscape and this made it difficult to objectively determine gully morphology. Only the clearly visible, large (depth >0.3 m) gullies were selected for detailed measurement. Gullies were divided into representative segments and for each segment length, top and bottom width were measured with a measuring tape. Depth was measured several times along each individual cross section in order to calculate cross-sectional area and gully volume. For each gully, only the maximum depth per segment was used to calculate mean gully depth. The respective mean value of each parameter for the whole gully was obtained by summing up the different segments. Each segment was weighted by its length. Gully volume was also obtained by summing up the different segment volumes. Width–depth ratio (WDR) was calculated as the ratio of mean gully top width and depth. Slope of the soil surface at the gully head (S_g) and slope of the soil surface where the gully ends by sediment deposition (i.e. sedimentation slope, S_s) were determined with a clinometer (type Suunto, error 0.005 m/m). Since gully heads may have retreated upslope since their formation (Nachtergaele et al., 2001), S_g was taken as the steepest slope along the gully trajectory. The runoff contributing area (A) was delimited with markers and measured in the field with a measuring tape.

In a third phase, the mapped gully location was compared with the zones where ephemeral gullies would be expected to form if the area was cleared for cropland. Only the large gullies that were measured in detail ($n=43$) are included in this analysis. The small gullies and road gullies are excluded. To predict gully location, mainly known equations were used. For the Belgian loess belt, several studies have fairly accurately predicted the position of ephemeral gullies under cropland, using only topographical parameters. Desmet et al. (1999) and Vandaele et al. (1996) worked in a catchment that is comparable to the Meerdaal Forest in terms of topography and soils. Therefore, the topographical threshold equations they proposed may be extrapolated to the Meerdaal Forest area. These equations are of the form:

$$S_g > aA^{-b} \tag{1}$$

with S_g the slope of the soil surface at the gully head (m/m), A the runoff contributing area (ha) and a, b are coefficients. These topographical attributes are derived from a grid-based DEM. The DEM (pixel size 5 × 5 m) was constructed by digitising and interpolating the 1:10.000 topographical map (NGI, 1972). Slopes were calculated with the SLOPE-module in IDRISI32 and the contributing area for each pixel is based on the multiple flow algorithm of Desmet and Govers (1996). Desmet et al. (1999) showed that Eq. (1) has to be written as:

$$S_g > a'A_s^{-b'} \text{ where } A_s = \text{the unit runoff contributing area } (\mathrm{m}^2/\mathrm{m}) \tag{2}$$

When A_s is derived from a grid-based DEM, the zones where ephemeral gully erosion can be expected to occur if the land-use was cropland, can be obtained using these threshold equations.

Depending on the value of the coefficients, two types of threshold equations can be distinguished: the first type predicts gully trajectories, whereas the second type predicts gully initiation points (Desmet et al., 1999). Apart from the published threshold equation coefficients, several new coefficients were used in the predictions in order to obtain a larger percentage of predicted pixels or higher efficiency. Prediction efficiency is defined as the ratio of the total number of correctly predicted gully pixels and the total number of predicted pixels.

4. Results and discussion

4.1. Spatial distribution of gullies in Meerdaal Forest

In total, 252 incisions were mapped, of which 82 were classified as small or large gullies and 170 as road gullies. Fig. 2 shows all mapped channel-like incisions within the study area. Of the 82 gullies, 39 were classified as small gullies and 43 as large gullies. As mentioned before, the small gullies were not analysed further because they are only poorly visible in the landscape. Nevertheless, their spatial distribution is very similar to that of the large gullies (Fig. 2). This distribution pattern can also be observed in fields that are under cultivation. During an erosive rain event, many rills can form, but only a few will develop into ephemeral gullies, because they capture more runoff than the other rills. Thus, the presence of these small gullies near large gullies indicates runoff production in their catchment. Besides the small and large gullies, a very large group of incisions ($n=170$) could be identified as old sunken lanes or road gullies.

In the field, several criteria were used to distinguish between large gullies and road gullies (Fig. 3). Road gullies are typically found on gentle slopes and have no or almost no drainage area. Furthermore, most road gullies are often found in groups, with an interval of 5–15 m separating them from each other. The distribution of the road gullies shows a linear pattern: most of them are aligned along straight,

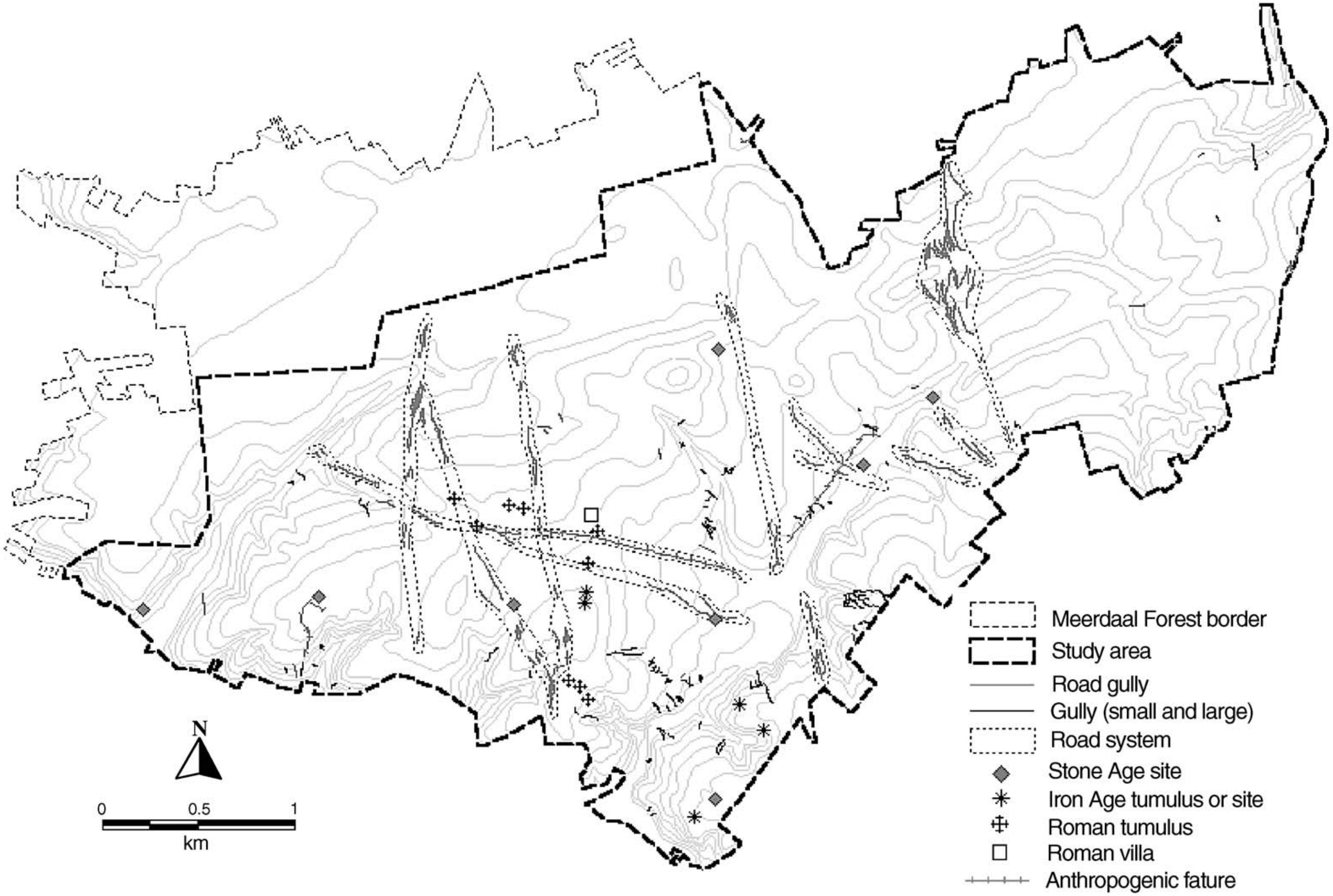

Fig. 2. Spatial distribution of the mapped incisions within the study area, with indication of the different identified road systems and the location of known archaeological sites. Several tumuli or burial mounds that are located immediately next to each other are indicated with only one symbol on the map.

Fig. 3. Illustration of two types of incisions in Meerdaal Forest: (A) large gully and (B) road gully. Note the typical V-shaped and trapezoidal cross-sectional profile of the large gully and the road gully, respectively.

north–south oriented directions (Fig. 2). The observed road gully pattern under forest is related to the location of the ‘anthropogenic features’, described earlier. They also show the same linear pattern as the road gullies. Together with the road gullies they are indicated in Fig. 2 as road systems (dashed lines) through the Meerdaal Forest.

The gullies, on the other hand, are more widely distributed, with the largest concentration in the southern part of the forest. To explain this distribution pattern, the relation with slope gradient, aspect, lithology and soil type was examined. Although the steepest slopes occur in the southern part of the forest, many steep slopes did not show traces of incision. Also with slope aspect, lithology or soil type, no clear spatial correlation could be found. The only correlation that could be established is when comparing the distribution of gullies with the pattern of known archaeological sites in the Meerdaal Forest (based on Martens, 1981), which are also located mainly in the south of the forest. In Fig. 2, the location of these sites in the study area is indicated. Four main periods of human occupation can be distinguished. Stone Age artefacts were found on several locations in the Meerdaal Forest but most of the sites are Iron Age or Roman tumuli or burial mounds. Apart from these burial mounds, no archaeological evidence exists that would indicate the presence of human settlements, large-scale deforestation or agriculture. Only at one location (Fig. 2) do some brick fragments suggest the possible presence of a Roman villa. In the 14th century, the forest obtained a special status of ‘Vrijwoud’, meaning that it could only be used for hunting purposes by the local nobility. Since then, it is certain that no large clearings have taken place. Nevertheless, the correspondence between the spatial distribution of gullies and that of archaeological sites yields a first indication that the distribution of the gullies is strongly related to very local anthropogenic disturbances of the forest cover, probably between Iron Age and Roman times.

4.2. Morphological and topographical characteristics

The morphological and topographical characteristics of the gullies and road gullies in the Meerdaal Forest are summarised in Table 1. The characteristics of typical ephemeral gullies formed under cropland (EG) in the Belgian loess belt, are also indicated for comparison (Nachtergaele, 2001).

The large gullies under forest differ significantly from the EG in all measured parameters, except bottom width. Also, most characteristics of the road gullies and large gullies under forest differ significantly from each other, except for the parameters length and bottom width ($\alpha = 5\%$). The length of EG is significantly ($\alpha = 5\%$) larger than both types of incisions under forest, although the standard deviation is large. The longest gully under forest is 214 m long and the shortest only 19 m. The longest ephemeral gully measured was almost 437 m long. These differences can be explained by the fact that forest gullies are often located on steep, short slopes. This indicates that the forest gullies are not always located in the same landscape positions compared to ephemeral gullies in cropland, which often occupy valley-bottom positions (Nachtergaele and Poesen, 1999). Gully-bottom width of EG does not differ significantly from the incisions under forest. However, gully depth (GD) and gully-top width (GW_t) of both gullies and road gullies is significantly larger than that of EG. The larger GD and GW_t of both types of incisions under forest compared with the EG results in a significantly larger cross section. This larger cross section compensates for the shorter length, so that mean gully volume (GV) is up to 30 times larger for the gullies under forest. The maximum individual cross-sectional area measured for

Table 1
Morphological and topographical characteristics of the large gullies and road gullies in Meerdaal Forest and ephemeral gullies under cropland in Central Belgium

	All incisions under forest			Gullies forest			Road gullies forest			Ephemeral gullies cropland (Nachtergaele, 2001)		
	n	Mean	SD	*n*	Mean	SD	*n*	Mean	SD	*n*	Mean	SD
GL (m)	64	64	45	43	64	50	21	65	33	58	191	252
GW_b (m)	64	1.10	0.50	43	1.11	0.55	21	1.09	0.39	58	1.63	1.38
GW_t (m)	64	6.95	4.00	43	8.10	4.20	21	4.60	2.20	58	1.63	1.38
GD (m)	64	1.04	0.89	43	1.26	0.98	21	0.59	0.41	58	0.19	0.13
WDR	64	8.05	3.1	43	7.66	2.9	21	8.9	3.5	58	22	29
GA (m^2)	64	6.16	8.9	43	8.13	10	21	2.1	3.2	58	0.18	0.12
GV (m^3)	64	69E^1	16E^2	43	94E^1	19E^2	21	16E^1	32E^1	58	31	30
S_g (m/m)	64	0.225	0.160	43	0.295	0.155	21	0.090	0.040	42	0.080	0.035
S_s (m/m)	58	0.080	0.050	37	0.100	0.050	21	0.045	0.020	35	0.025	0.015
A (ha)	52	0.126	0.168	38	0.154	0.187	14	0.051	0.053	42	1.422	2.198

Data for ephemeral gullies were collected by Nachtergaele (2001).
GL = gully length; GW_b = gully width at bottom; GW_t = gully width at top; GD = gully depth; WDR = width – depth ratio of gully (= GW_t/GD); GV = gully volume; GA = gully cross section; S_g = slope of soil surface at gully head; S_s = sedimentation slope.

gullies under forest was 97.1 m^2. The maximum gully depth of 7.80 m and also the largest top width of 24.00 m were measured in this cross section. Ten of the 43 forest gullies have volumes >1000 m^3, the largest eroded gully volume measured is 99E^2 m^3. Only one road gully had a volume >1000 m^3. This difference in GW_t and GD between the different types of incisions is also reflected in the width–depth ratio, which is almost the same for gullies and road gullies under forest, but significantly higher for EG under cropland. The reason for the larger cross section and larger eroded volume for the incisions under forest is probably that EG are formed during one or two seasons with erosive rain events, after which they are erased by ploughing, whereas incisions under forest could develop during many years. Nachtergaele et al. (2002) studied an ephemeral gully that was not erased by ploughing after its formation and which developed into a permanent gully. They observed an increase of gully size during the first few years, then gully volume started to decrease, because sediment was captured by vegetation growing in the gully bottom. The gullies under forest have probably never reached this last phase of infilling or experienced only a limited infilling, because runoff and sediment production in the catchment area was cut off by a change in the land-use (e.g. cropland to forest). Another important difference between old incisions under forest and recent ephemeral gullies under cropland is the cross-sectional shape. In recent gullies under cropland, gully walls are vertical or even overhanging. Even in gullies that had formed 10 years before, walls were still vertical (Nachtergaele et al., 2002). This results in a rectangular shaped cross-sectional area for ephemeral gullies. Gullies under forest, however, have typically V-shaped cross-sectional areas (Fig. 3a). Mean gully wall gradients of 0.460 m/m were measured. The maximum observed gradient was only 0.820 m/m, which is still far from vertical. Road gullies typically have a trapezoidal cross section, but their wall gradients were not quantified. Besides the fact that in the thalweg of the large forest gullies and road gullies, sometimes trees of over 100 years old can be found, their cross-sectional shape is an important indication suggesting these incisions cannot be recent. As a conclusion, it can be stated that a morphological differentiation between gullies and road gullies under forest is possible, but not always very pronounced, while both types of incisions under forest differ significantly from EG, which form under cropland conditions.

When comparing the slope of the soil surface at the gully head (S_g), which approximates the slope at which the gully initiated, for the three types of incision, it can be seen that forest gullies are clearly located on steeper slopes compared to the EG and the road gullies, that have almost identical S_g values. The difference in S_g between the forest gullies and the EG is significant at the 5% level, while no significant difference could be demonstrated between S_g of road gullies under forest and EG. A similar conclusion can be drawn for S_s. The forest gullies typically end at a mean soil surface slope of 0.10 m/m, which is even more than the mean slope at which road gullies and EG start to incise (0.090 and 0.080 m/m, respectively). Although the difference in S_s between road gullies under forest and EG is small in absolute terms (0.010 m/m), in this case however the differences between the three types are significant ($\alpha = 5\%$). This can be seen more clearly in Fig. 4, which shows the frequency distribution of the sedimentation slopes of the gullies under forest, the road gullies under forest and the ephemeral gullies under cropland. Besides topography, the slope at which sedimentation occurs is influenced by rock content (Poesen et al., 2002) and vegetation (Beuselinck et al. 2000). Since topsoil rock content is very low for soils in the Meerdaal Forest, the different sedimentation slopes must be controlled by either topography or vegetation. The fact that gullies under forest have steeper sedimentation slopes could thus indicate that sedimentation was not purely topographically controlled, but was promoted by the presence of vegetation on the eroding slopes. This is another important indication that these gullies were caused by human disturbances of the forest vegetation in the gully catchment. If cultivation had occurred in Meerdaal Forest, it is easy to imagine that while locally the plateau positions were deforested, the adjacent steep slopes would have remained vegetated because soils are less fertile and difficult to cultivate. In this way, Hortonian runoff generated on the plateau could then easily erode the gullies on the forested slopes. Since these slopes were vegetated, sedimentation occurred at steeper slopes compared with bare cropland slopes. Sedimentation slope of road gullies on the other hand, which have a completely bare surface due to trampling of humans and animals, is

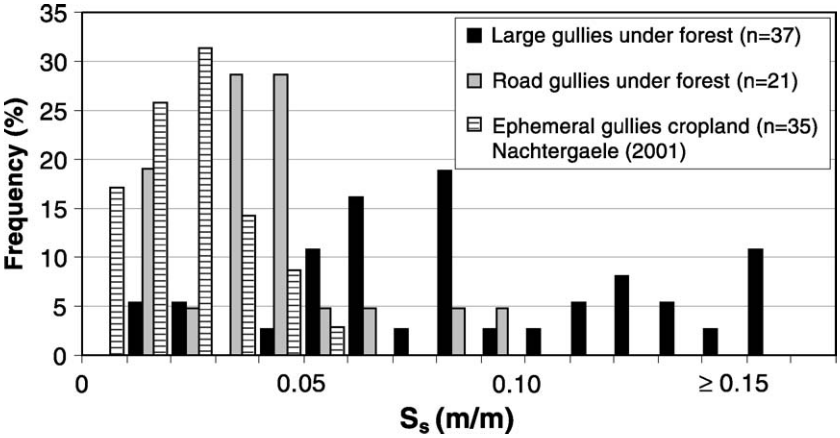

Fig. 4. Frequency distribution of sedimentation slope (S_s) of gullies and road gullies in Meerdaal Forest and ephemeral gullies under cropland in Central Belgium. Data for ephemeral gullies were collected by Nachtergaele et al. (2001).

more comparable to the situation of ephemeral gullies under cropland, where vegetation cover is minimal and sediment deposition is essentially controlled by local topography. The runoff contributing area (A) of the forest road gullies is very small ($A = 0.051$ ha), which again points to their anthropogenic genesis. Also A of the forest gullies is almost one order of magnitude smaller compared with A for EG. Fig. 5, showing the relation between S_g and A for the forest gullies, the road gullies under forest and the ephemeral gullies under cropland, yields more insight into their formation. The main water erosion processes on arable land in the Belgian loess belt are driven by Hortonian overland flow. Studies (e.g. Patton and Schumm, 1975; Montgomery and Dietrich, 1994; Nachtergaele et al., 2001) demonstrated that under Hortonian overland flow a negative power relation between S_g and A is expected (Eq. (2)). For this dataset, it could however be statistically demonstrated that no correlation exists between S_g and A. According to Montgomery and Dietrich (1994), this could indicate that gully formation is affected by other processes, such as saturation overland flow or landsliding. However, no evidence for the presence of exfiltration processes was observed in the study area, although field mapping occurred in a very wet year. Also, the physical conditions for landsliding are absent. There is no soil horizon or geological layer that could function as a potential shear plane. The only explanation that can be given for the absence of correlation between S_g and A is that the forest gullies are located on very steep slopes. Thus, it is reasonable to assume that drainage area plays only a minor role and the relative importance of slope in gully erosion is much larger. Therefore, for a given slope gradient, gullies can be formed within a range of runoff contributing areas and these can even be quite small compared with EG formed under cropland.

When comparing the data points corresponding to the road gully heads with those corresponding to the forest gullies, it can be seen that they form two clearly distinct groups. As discussed above, the road gullies are generally on more gentle slopes and have little runoff contributing area. Since the road gullies are anthropogenically determined, and not purely topographically, it is logical that there is no correlation between S_g and A.

The gullies under forest also form a separate group when compared with ephemeral gullies formed under cropland conditions (Nachtergaele et al., 2001). Fig. 5 indicates that the forest gullies are not always located in the same landscape positions compared to the ephemeral gullies in cropland. This discrepancy is most probably linked to a difference in position of runoff-producing areas: i.e. under forest, locally cleared plateau positions draining to steep slopes where the forest gullies developed, whereas in the case of cropland, completely cleared zero-order catchments, leading to the development of ephemeral gullies in valley-bottom positions.

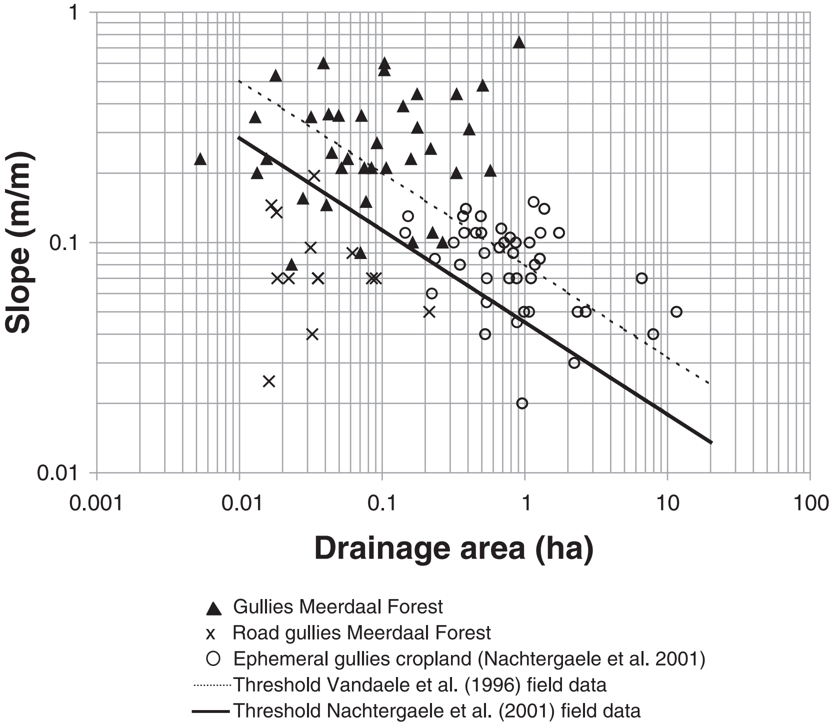

Fig. 5. Relation between slope of the soil surface at the gully head (S_g) and runoff contributing area (A) for the gullies and road gullies in Meerdaal Forest and comparison with ephemeral gullies under cropland in Central Belgium.

The critical topographical threshold lines that are indicated in Fig. 5 were established for ephemeral gullies under cropland in Central Belgium on the basis of field data collected by other authors. Topographic positions plotting below these threshold lines are stable and no gully incision is expected to occur, whereas gully erosion can be expected in landscape positions plotting above these lines. It has to be mentioned that for comparative purposes these lines have been extended in the graph outside the range of data points on the basis of which they were originally drawn. Nevertheless, although these thresholds are established for cropland, most points corresponding to the forest gullies are located above these lines. When considering, for example, the threshold line established by Nachtergaele et al. (2001), 31 of the 38 forest gully points are located above this threshold. Thus, although S_g and A for the two gully types are different, the combination of S_g and A seems to compensate for this difference and the forest gullies do generally not occur below the topographical threshold line established for ephemeral gullies under cropland.

4.3. Prediction of gully location

Under the hypothesis that the whole of Meerdaal Forest was cleared and used as cropland in the past, Fig. 6 shows the zones (in grey) where gully trajectories are expected to occur, using the topographic thresholds for ephemeral gully development established by Desmet et al. (1999). The mapped gullies are shown in black. In the southern part of the forest, where most gullies are concentrated, mapped gully position coincides fairly well with the zones where gullies are expected to occur. However, it can be seen that the overall prediction is not so good because in a large part of the study area, especially in the north, gully erosion is predicted to occur, but no gullies are present. This results in a low prediction efficiency. This is an observation that is valid for all the different threshold equations that were used (Table 2). The

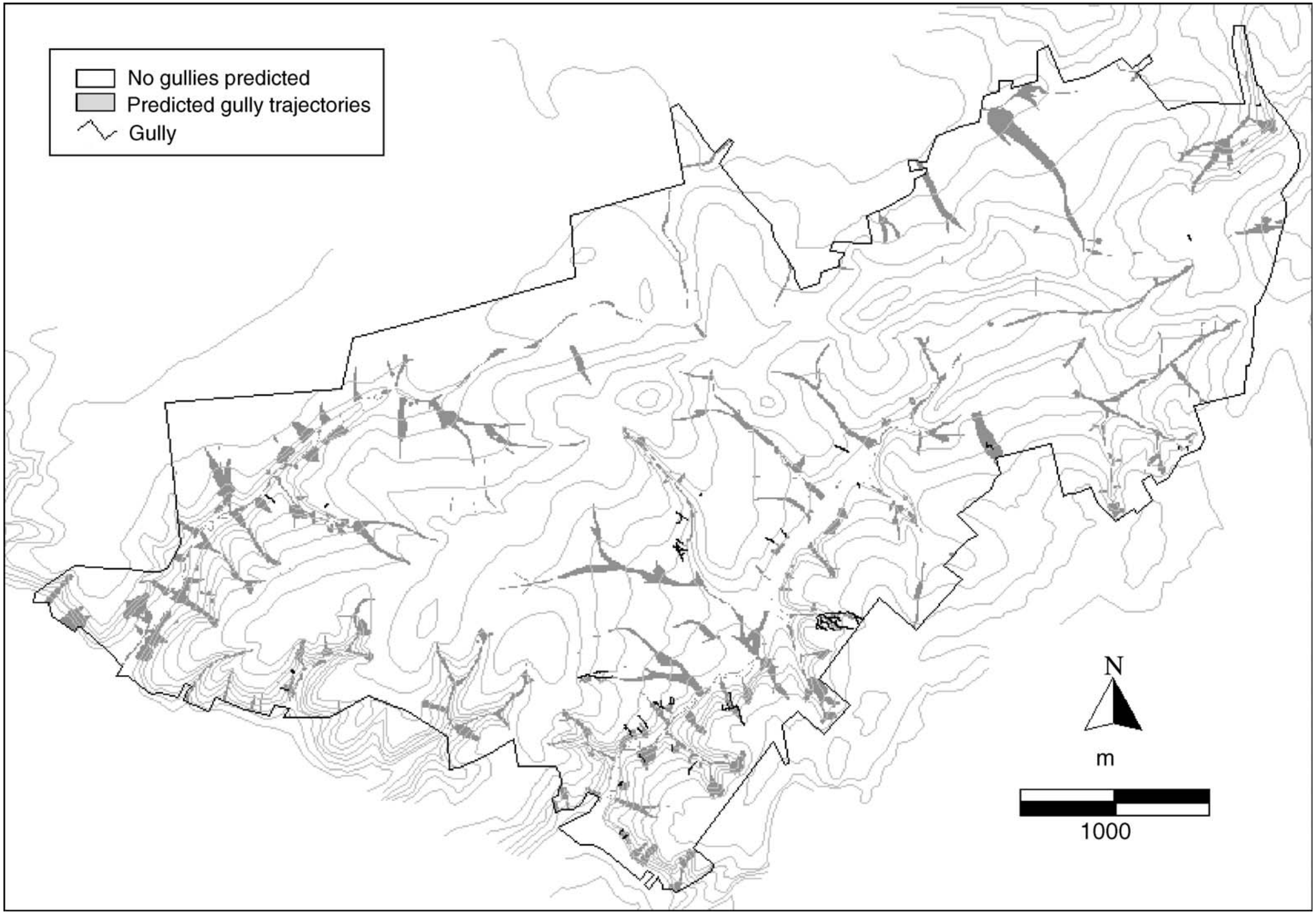

Fig. 6. Prediction of (ephemeral) gully trajectories based on the topographic thresholds proposed by Desmet et al. (1999) for the catchment of Hammeveld (Central Belgium), with similar topographical and lithological characteristics as the Meerdaal Forest. $S_g > a' A_s^{-b'}$ with S_g = slope of soil surface at gully head (m/m); A_s = unit runoff contributing area (m^2/m); $a' = 33$ and $b' = 1$.

Table 2

Prediction of ephemeral gully trajectories or ephemeral gully initiation positions based on topographic thresholds established by several authors ($S_g > a'A_s^{-b'}$) with S_g = slope of soil surface at gully head (m/m); A_s = unit runoff contributing area (m^2/m) and a', b' are coefficients

Pixel size	5 × 5 m
Total area (ha)	1329
Total number of pixels corresponding to study area	533 823
Total number of mapped gullies	43
Total number of gully pixels	764

	Source	Coefficients	Total number of predicted pixels	Number of gully pixels correctly predicted	% of total study area predicted	% of gully pixels predicted	Efficiency of prediction[a] (%)
Prediction of gully trajectory	Desmet et al. (1999) Kinderveld	$a' = 52.5$; $b' = -1$	23 699	109	4.4	14.3	0.46
	Desmet et al. (1999) Hammeveld	$a' = 33$; $b' = -1$	37 258	162	7.0	21.2	0.43
	Desmet et al. (1999) adapted[b,c]	$a' = 18$; $b' = -1$	76 851	310	14.4	40.6	0.40
	Desmet et al. (1999) adapted[c]	$a' = 15$; $b' = -1$	96 487	357	18.1	46.7	0.37
Prediction of gully initiation location	Vandaele et al. (1996)	$a' = 0.486$; $b' = -0.4$	144 210	615	27.0	80.5	0.43
	Vandaele et al. (1996) adapted[d]	$a' = 0.55$; $b' = -0.4$	119 945	571	22.5	74.7	0.48
	Vandaele et al. (1996) adapted[d]	$a' = 0.7$; $b' = -0.4$	84 238	462	15.8	60.5	0.55
	Vandaele et al. (1996) adapted[d,e]	$a' = 0.874$; $b' = -0.4$	59 196	349	11.1	45.7	0.59
	Desmet et al. (1999) DEM	$a' = 1.15$; $b' = -0.4$	34 170	193	6.4	25.3	0.56

[a] Efficiency of prediction = total number of gully pixels correctly predicted/total number of predicted pixels × 100.

[b] This relation equals part of the threshold equation proposed by Moore et al. (1988).

[c] Adaptation of coefficient a' in threshold equation Desmet et al. (1999) in order to improve number of gully pixels correctly predicted.

[d] Adaptation of coefficient a' in threshold equation Vandaele et al. (1996) in order to improve efficiency of prediction.

[e] This relation equals the threshold equation proposed by Nachtergaele et al. (2001).

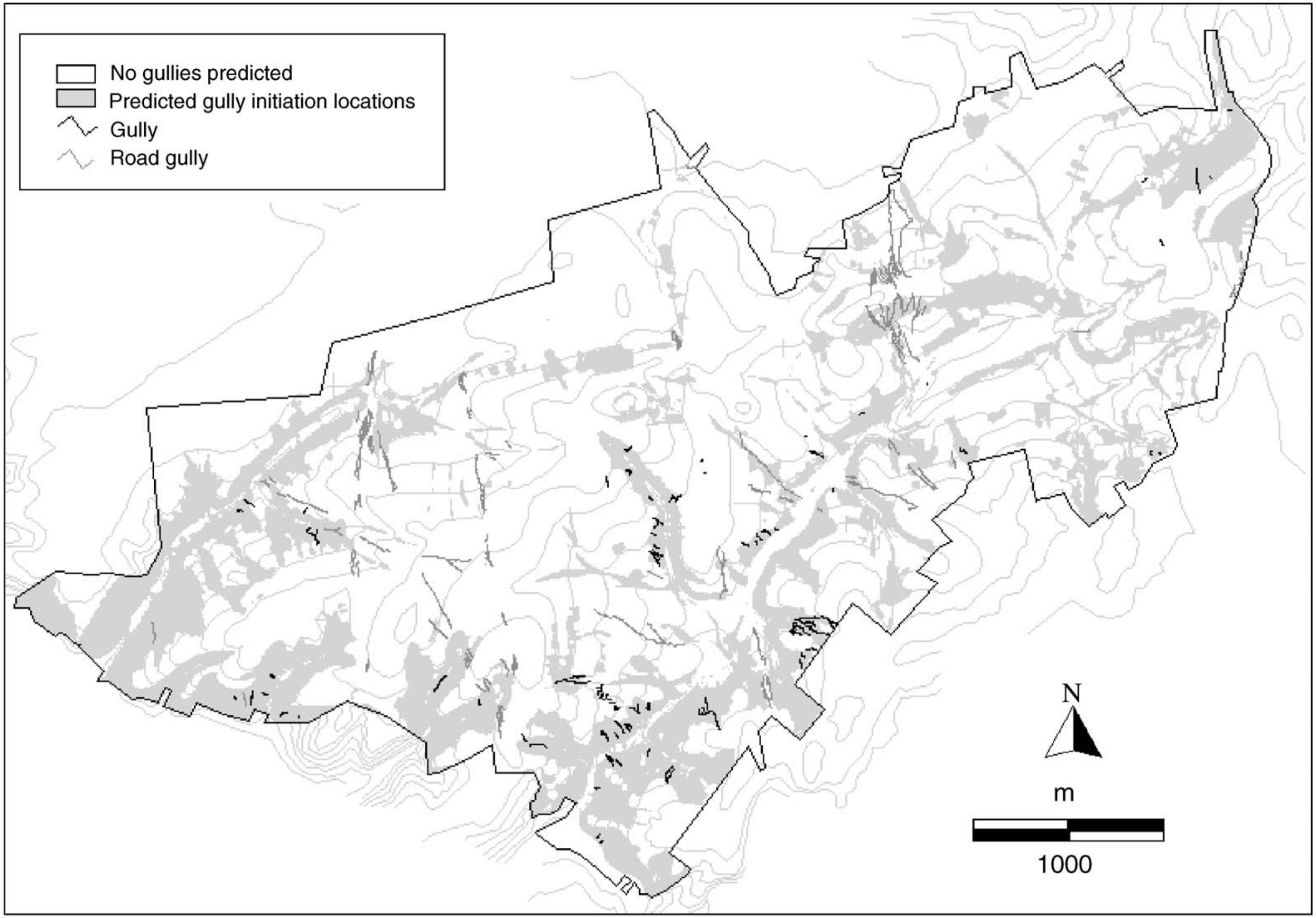

Fig. 7. Comparison of predicted zones where ephemeral gullies are expected to develop under cropland with mapped gullies and road gullies in the Meerdaal Forest. Prediction of gully initiation locations is based on the topographic threshold proposed by Vandaele et al. (1996): $S_g > a'A_s^{-b'}$ with S_g = slope of soil surface at gully head (m/m); A_s = unit runoff contributing area (m^2/m); a' = 0.486 and b' = 0.4.

highest proportion of gully pixels that could be correctly predicted is somewhat more than 80%, but 27% of the total study area has to be predicted as prone to gully erosion (threshold equation by Vandaele et al., 1996). Thus, this relatively low prediction efficiency (overall < 1%) is not necessarily because the mapped gullies are not predicted correctly, but more because all the simulations predict many large zones where no gullies are observed.

It is not clear why many zones are predicted as being susceptible to gullying, whereas no gullies are observed. The best explanation is probably that predicted zones where no gullies are found were never deforested. Forest zones where gullies were mapped can be predicted by the same topographic threshold relations that are valid for prediction of ephemeral gullies under cropland. Therefore, it is reasonable to assume that these zones were locally cleared and used for cropland, charcoal production, animal grazing, or any land-use that disturbed the permeable forest floor. Subsequently, ephemeral gullies could form and evolve to larger, permanent gullies after which the area was reforested. Future research, focussed on some case studies, needs to indicate the timing and nature of the land-use disturbance that initiated gully erosion. The possibility that extreme rainfall events caused severe gully erosion seems invalid. Firstly, most gullies are concentrated in the southern part of the forest, and this corresponds very well with the distribution pattern of archaeological sites, as mentioned earlier. Also, the prediction of many zones prone to gullying where no gullies are observed indicates that an extreme event did not cause gully incision. Similar arguments can also be applied to explain why it is difficult to assume that the gullies formed under periglacial conditions. Moreover, if the gullies are not of anthropogenic origin, but the result of natural periglacial erosion processes, one would expect a spatial distribution that reflects systematic patterns or a clear correlation with slope gradient, aspect or lithology. As shown above, this relation could not be found.

When comparing the zones in the forest where ephemeral gully erosion can be expected with the position of the road gullies, another interesting observation can be made. This is illustrated in Fig. 7 with the threshold relation of Vandaele et al. (1996) which predicts the highest percentage of gully pixels correctly (i.e. 80.5%), but also predicts almost one third of the total study area (i.e. 27.0%) as being susceptible to incision by ephemeral gullies (Table 2). However, practically all the road gullies are located outside these predicted zones. This indicates that the location of the road pattern was not random. Since man chose the easiest trajectory (and thus with a low gully erosion risk because of gentle slopes) to cross the hills, the road gullies are located outside the predicted zones where gullies are expected to occur. This method also provides extra evidence to distinguish between gullies and road gullies.

5. Conclusions and implications

The analysis of the spatial distribution, the morphological and the topographical characteristics of the large forest gullies and the modelling results of the location of ephemeral gullies in a cleared forest, indicate that the forest gullies were caused by local disturbances of the forest cover on the plateau positions. These plateau positions were very suitable for use as cropland, whereas the slopes were left vegetated because cultivation is difficult and, in some cases, the fertile loam cover overlying the Tertiary sands is very shallow. Nevertheless, large gullies could develop on these forested slopes. These gullies did not immediately hinder further cultivation of the plateau positions and several runoff-producing events could deepen and widen them. However, before the gully could fill in naturally by sediment deposition, the forest on the plateau was re-established, thus cutting off runoff and sediment production in the drainage area. The hypothesis that extreme rainfall events caused runoff and erosion under a protective forest cover proved highly unlikely. Also, the hypothesis that the gullies were formed before the establishment of a forest vegetation in a periglacial environment could not explain their spatial distribution pattern.

This study shows that modelling gully location based on knowledge of ephemeral gully erosion under cropland is a useful tool for assessing the controlling factors of past gully development. This study also indicates that even in forested areas, which were thought to represent natural conditions, human impact has been important in the past. The traces (i.e. the forest gullies) of these old human-induced land-use changes are still conserved under the protective forest cover and therefore these areas are of unique value. More research is however needed to date the main land-use changes and erosion phases.

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