

Research Article

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Dynamics of gully side erosion: a case study using tree roots exposure data

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Abstract: Erosion is a frequently studied natural process. Unfortunately, detailed analysis mostly requires long-term field monitoring or detailed digital elevation models (DEM) which are still absent for many areas. For these reasons we used the dendrogeomorphic method, a valuable tool for erosion analysis. The slopes of a ~220 m long gully close to the Kozárovce village (Slovakia) were the object of our study. We analyzed 53 tree root samples coming from 16 broad-leaved trees of different species. 23 erosion event years were explored during the reconstruction period AD 1972–2013. The mean erosion rate E_R was 1.00 cm/year. We were able to create four erosion patterns of slope erosion based on subsequent exposure of different parts of root. These erosion patterns serve as a base for a model of gully cross profile development. The highest values of erosion rate were reconstructed in the lowest parts of gully slopes. The gully sides formed by volcanic rocks are affected by lateral retreat here. Upward erosion dominates in the middle parts of slopes in loess, and downward erosion in the highest parts of the slopes.

Keywords: dendrogeomorphology; slope erosion; gully; loess

1 Introduction

Erosion is a dangerous geomorphic process and therefore a natural hazard [1]. A high variability of erosion processes divisions exist (water and wind erosion, or sheet and gully erosion) [2, 3]. According to [4], water and wind erosion exists in Slovakia, where one type of water erosion process is

gully erosion. On the one hand, gully erosion causes soil degradation, river aggradation and aggradation of natural and anthropogenic dam [5, 6], when their retention capacity and basic functions can be reduced. On the other hand, soil erosion as a geomorphological process is producing new forms of land surface e.g. ephemeral or permanent gullies. Gullies increase the geodiversity of landscape and can be the object of protection. The main object of interest is the intensity of the process itself which is quantified by deepening, widening and elongation of gullies [7]. An important topic is the quantification of eroded material as an input into the total sediment budget [8]. This information has become crucial for verification or calibration of mathematical models of development of the land surface. A specific cross profile of gullies is result of mentioned processes. The intensity and direction of erosion is also controlled by soil or weathering mantle thickness and bedrock lithology [9].

The dangerousness and the practically global extent of erosion processes is the reason why many different methods of eroded material quantification were developed. Three groups of methods can be distinguished. Methods based on long-term observations create the first group. One of the most popular methods from this group is the installation of dense network of erosion pins e.g. [10]. Other methods are based on installation of devices measuring sediment outflow from sub-basins e.g. [11]. The second type of methods is based on quantification of eroded landforms volumes using differential DEM. Models are constructed using geodetic measurements, photogrammetry e.g. [12, 13] or laser altimetry [14]. The third type of methods is based on mathematical models of erosion processes e.g. [15, 16].

A suitable method for erosion study is dendrogeomorphology [10]. If the wood anatomy is taken into account, it can provide very detailed and precise results [17, 18] with annual resolution covering up to several decades [9]. This method is very suitable in the case of long-term field monitoring absence and in the localities with presence of exposed tree roots. The method is based on the fact that trees build one increment ring each year. Tree(root)-rings are able record external disturbances (e.g. root exposure)

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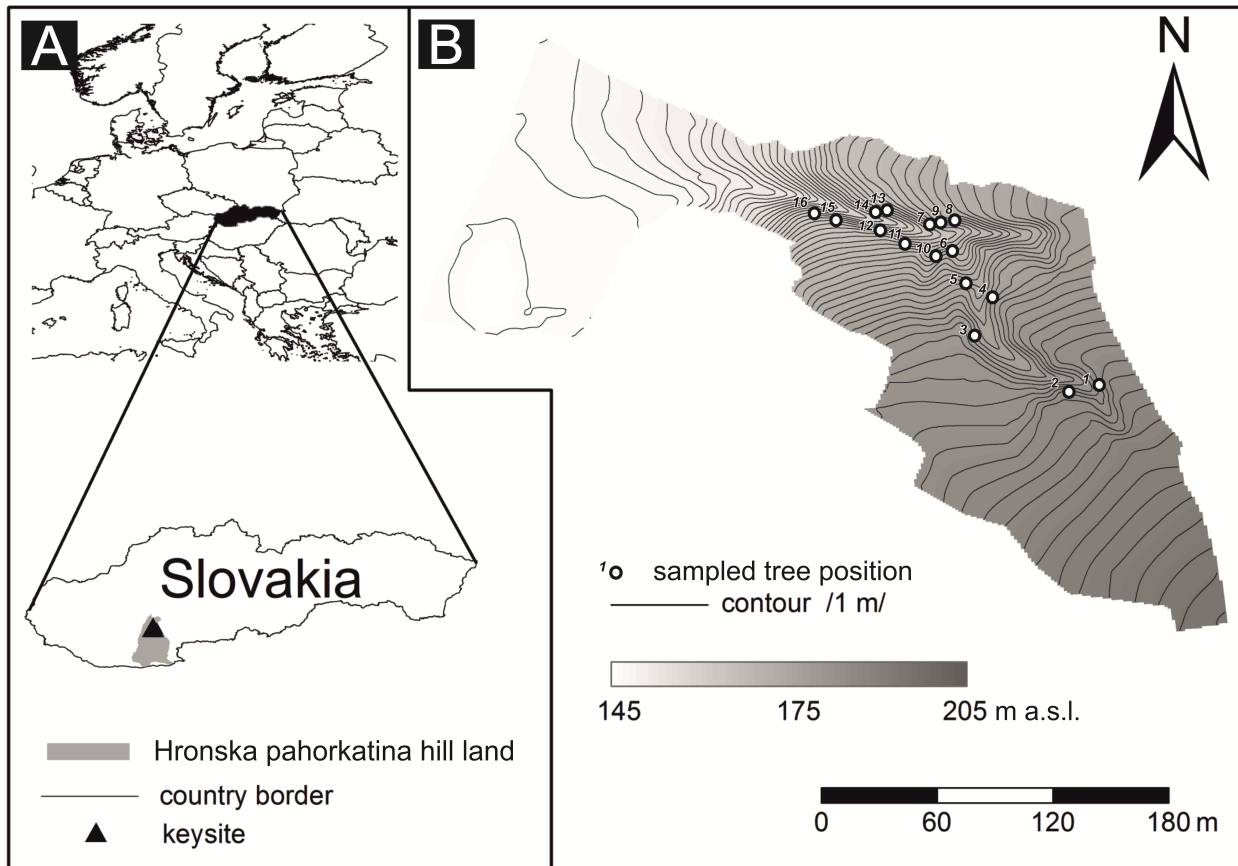


Figure 1: Location of studied area in the Slovakia (A) and detailed model of studied gully system (B).

in their growth and anatomy. Different anatomical and growth responses occur in different groups of trees (broad leaved and coniferous) on their roots exposure. Generally the reactions of broad leaved trees are more complex and include several microscopically and macroscopically visible features. The differences in anatomical reaction even occur between diffuse porous and ring porous species [19]. Moreover, the precise position of samples must be recorded. Dendrogeomorphology and tree-roots were successfully used for analysis of spatio-temporal activity of debris flow [20, 21], rockfall [22, 23], landslides [24–26], floods [27–30] and erosion processes [31, 32]. *E.g.* [7] presented a detailed study about using of tree roots exposure for quantification of gully erosion. Several authors work with tree-ring width changes (and eccentric growth) as an indicator of root exposure [e.g. 32–35]. Erosion processes and erosion forms (particularly gullies) in Slovakia have occasionally been studied [2–4]. Nevertheless, precise dendrogeomorphic research of gully development was not realised here yet. Knowledge about historical gully development is limited to aerial photographs or archival records study.

The main aims of this study (using dendrogeomorphic methods) are (i) reconstruction of erosion processes on gully slopes with different lithological bedrock (loess × volcanic rocks), (ii) building the chronology of erosion events, (iii) determination of the intensity of erosion and (iv) the creation of the local gully side development model.

2 Studied area

The key site is situated in southwest Slovakia, on the border between Hronská pahorkatina Hill Land and Štiavnické vrchy Mountains (Figure 1A; eastern from the Kozárovce village). The most precise information about climatic conditions is provided from the climatological station Mochovce (Slovak Hydrometeorological Institute) situated 16 km from the locality. The average annual temperature is 9.8°C (20.1°C in July and –1.2°C in January). The average daily precipitation is 5.3 mm in July, 2.7 mm in January, and 3.8 mm for whole year. Maximal average intensity of rain is in July at 0.1 mm/hour.

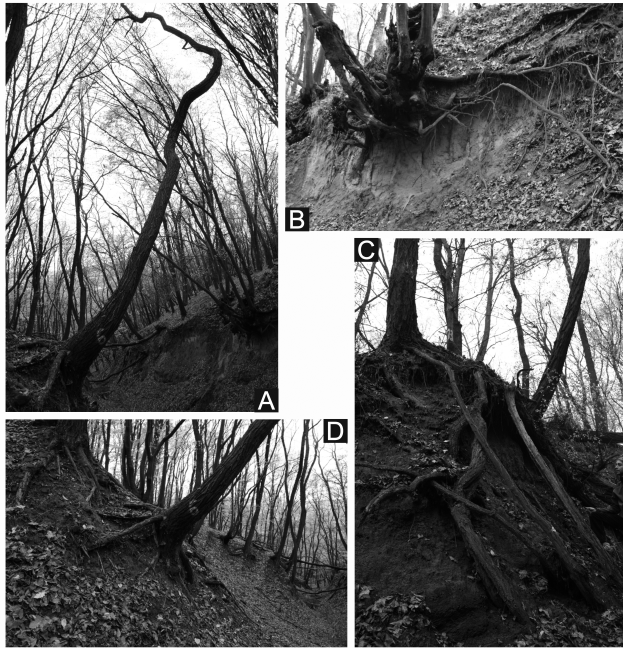


Figure 2: Morphology of eroded slopes and trees (A – abrupt growth changes of tree stem direction due to destabilisation of its base, B – eroded slope on loess sediment, C – exposed tree roots on volcanic bedrock slope, D – destabilized tree stem due to slope erosion).

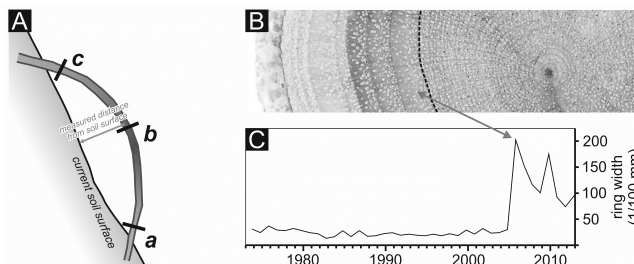


Figure 3: Methods used for roots sampling and exposure identification (A – position of root sampling and distance from soil surface measuring, B – growth response on root exposure – *R. pseudoacacia*, C – increment curve of root rings with visible growth release as reaction on exposure).

The studied gully is one from the whole system of gullies situated on the left river Hron bank. The system of gullies has been already mapped on military maps constructed between 1782 and 1784. The gully consists of one main gully ~220 m long with maximal width of 14 m and two smaller branches (Figure 2B). The maximum depth of system is 6 m and the total catchment area is 17 520 m². The bedrock consists of compact pyroxene andesite, outcropping in a down part of the gully system. The volcanic rocks are overlaid by deluvial loess and loess loam. The gully morphology can be divided into three parts. The first

part consists of the long branch of the gully system in a south part of locality. The second part consists of a shorter branch in the north, and the third part is formed by the main part of gully system, where both branches confluence.

We have no direct information about the development of the vegetation in the locality. According to old military maps from 1782–1784, 1819–1958 and 1857–1883 (with unknown spatial accuracy) we can assume that the main body of current gully was continually covered by forest from at least 1782 up to the present day. The less steep part of surface near the gully head was deforested in the past and is now exploited as a vineyard. Slopes around the gully system are covered by oak (*Quercus petraea* Matt., Liebl.), European hornbeam (*Carpinus betulus* L.), Small-leaved Lime (*Tilia cordata* Mill.) and False Acacia (*Robinia pseudoacacia* L.) (Figure 2). The upper part of the catchment is used as arable land.

3 Materials and methods

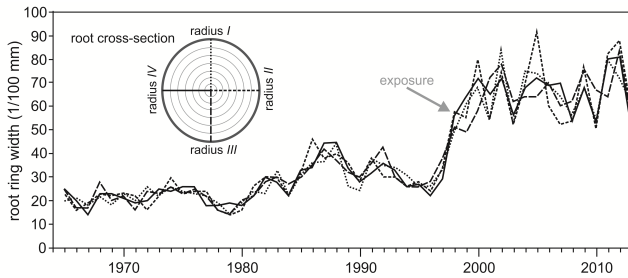
3.1 Dendrogeomorphic methods

Exposed tree roots, growing on the gully sides, were sampled during 2013 (only on the lateral side of the gully channel). A hand saw was used to extract approximately two cm-wide cross-sections from different position on the exposed roots. The basic sampling position on any given root occurred on both ends where the root makes contact with soil and where the distance between the root and soil was the longest (Figure 3A). This means that at least three samples were taken from each root. The distances of sampled roots were at least 0.5 m from tree base. The position of each sample was very carefully recorded and the perpendicular distance from soil measured (Figure 3A). Only roots with vertical direction were sampled in order to exclude problems with partial exposure due to the “dam effect” of gravitationally moved soil [9]. The lithology of root bedrock was visually identified and recorded as well.

The samples were dried for approximately one month, and the surface was subsequently sanded (sandpapers with 80–1000 grains) and polished. The growth reactions needed to identify the moment of exposure were visible on all of the prepared root samples. In some cases, the anatomical reaction was visible. Tree-rings were then counted, and their widths measured using a positioning dendrochronological timetable with PAST4 software [36] (Figure 3). Several radii on each disc were measured. Finally, tree-ring series were cross-dated among each other

Table 1: Number of samples and age structure of all sampled tree species.

	Samples (%)	Age (years)			Sample diameter (cm)	
		Minimal	Maximal	Mean (stdev)	Mean (stdev)	
<i>R. pseudoacacia</i>	11 (21)	22	45	34.5 (7.0)	6.8 (1.4)	
<i>C. betulus</i>	26 (50)	19	55	29.4 (10.2)	7.1 (1.8)	
<i>Q. petraea</i>	9 (17)	22	48	30.9 (8.4)	6.5 (1.9)	
<i>T. cordata</i>	6 (12)	15	26	19.8 (4.5)	4.6 (1.1)	
Total	52 (100)	15	55	29.9 (9.4)	6.6 (1.8)	

**Figure 4:** Example of cross-dated growth increment curves in four different radii on root cross-section.

to identify and correct false/missing or wedging rings (Figure 4). The quality of cross-dating was verified using graphical functions of the PAST4 software [17].

In general, the coniferous species (e.g. *P. abies*) reacts on exposure by reduction of the lumen area of earlywood tracheids (approximately 50%) [18]. On the other hand, the latewood tracheids increase cell wall thickness. The widening of tree-rings and the formation of classical structures of early and late wood (such as on a stem) usually follow the exposure [37], although cases of pre-exposure occurrence can be observed [17, 32, 38]. The growth reaction in roots of broad-leaved trees on exposure (in comparison with the coniferous trees) consists of earlywood vessels and fibre cells reduction [39]. Reaction wood (as a growth response to exposure) can occur in both tree groups as well [9].

The dating of root exposure was based on some basic growth signals which were identifiable by macroscopic analysis of prepared tree roots surfaces. It was abrupt eccentric growth in the case of broad-leaved trees, evidence of reaction wood formation (Figure 3), occurrence of callus tissue and formation of rings with similar anatomical structure as in the stem tree rings. Several authors work with the changes of ring width as evidence of their exposure [e.g. 33], but often for continuous sheet erosion. In our case, we used the approach for dating of individual erosion events likely caused by some triggering hydrometeorological event. In some cases, when the ring widths

were higher (~5 mm and more), it was possible to identify some anatomical features regarding to exposure (particularly above mentioned vessel size changes) under binocular microscope. Otherwise, microscopic analysis of microsections is still necessary, particularly for analysis of continuous erosion.

The erosion rate (E_r) for the position of each root was calculated following:

$$E_R = D_R/A_E \quad (1)$$

where D_R is the perpendicular distance of the root sample from the soil surface, and A_E is the number of years since the root exposure.

4 Results

4.1 Sampled tree species, number and age of samples

In total, 52 samples from the roots of 16 trees were extracted, prepared and analysed. The largest number of samples came from *C. betulus* (29 root samples) and the fewest from *T. cordata* (only 6 root samples). The other sampled tree species were *R. pseudoacacia* (11 samples) and *Q. petraea* (9 samples). Fourteen samples (from four trees) were situated in the first part of gully, 23 samples (from six trees) in the second part of gully and 15 samples (from six trees) were located in the third part of gully. The mean age of all samples was 29.9 years (stdev: 9.4 years). The oldest sample has 55 tree-rings (*C. betulus*) whereas the youngest sample has only 15 tree-rings (*T. cordata*). Details about the sampled tree species and the age of samples are shown in Table 1.

4.2 Chronology of erosion events/years

For the whole reconstructed period (41 years), 23 years with root exposure were identified. All exposures can be

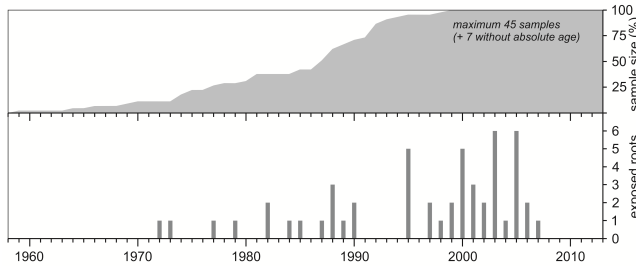


Figure 5: Tree roots exposure as a proxy for chronology of erosion events.

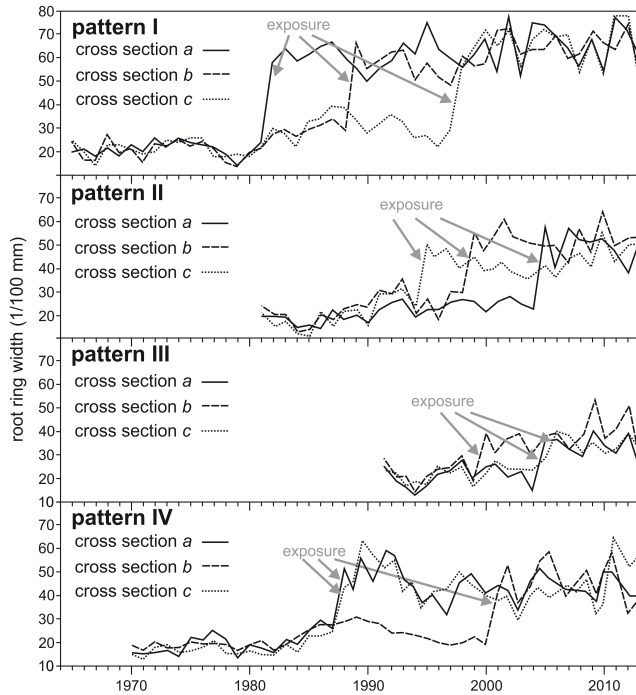


Figure 6: Example of root section exposure in all erosion patterns.

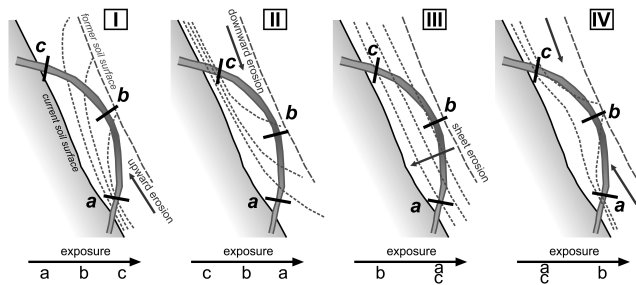


Figure 7: Reconstructed erosion patterns based on chronology of samples exposition (a, b, c – samples).

defined as abrupt, as the absence of microscopic analysis does not allow identifying continuous root exposure. The mean recurrence interval between two subsequent erosion events is 2.4 years. The oldest root exposure occurred in AD 1972 whereas the youngest in AD 2007. The most roots were

exposed in AD 2003 (six samples) and in AD 2005 (six samples). Eleven event years were determined based on just one exposed sample. The mean number of exposed root samples during each erosion event was 2.2. The chronology of erosion events/years can be divided into two different periods (Figure 5). The first period (1972–1990) is typical with a low number of exposed samples during each erosion year (mean = 1.4 exposed samples per event). Five years without any dated root exposure ensued after this period. The second period of erosion events/years (1995–2007) is typical with a higher number of exposed samples in comparison with the first period (3.0 exposed samples per event). No sample exposures were dated to the last six years (since AD 2007).

4.3 Erosion rate and types of erosion patterns

Based on the date of exposure of individual samples from each root, four erosion patterns of slope development were created. The patterns were built based on the chronological order of individual samples exposure from one root (Figure 6, 7). Pattern I (Figure 7A) is characterized with typical upward erosion. The roots are subsequently exposed in the uphill direction. The opposite situation is typical for pattern II (Figure 7B). It is characterized with downward erosion. The roots are subsequently exposed in the downhill direction. The gully side with erosion pattern III (Figure 7C) is developed due to process of sheet erosion. As the first, the sample that is the farthest from the current soil surface is exposed. The other two samples are always exposed practically in the same year (maximal real difference: 2 years; mean difference: 1.25 years). Erosion pattern IV (Figure 7D) is combination of pattern I and II. At first the two closest samples to current soil surface are exposed and after that the farthest sample. Erosion pattern II is the most prevalent (seven cases) with patterns I and IV less frequent (both only three cases). The highest erosion rate is typical for pattern III (mean: 1.27 cm/year) and the lowest rate for pattern I (mean: 0.82 cm/year). Details about the erosion rates in the cases of individual erosion patterns are in Table 2.

4.4 Slope lithology vs. erosion patterns/rate

Slope erosion occurs in two types of material. The bedrock in the lower parts of slopes is built by volcanic rocks (pyroxene andesite) whereas the upper parts of slopes are covered by loess material. Samples from four trees (12 root

Table 2: Erosion patterns and erosion rates.

Erosion pattern	Number	Erosion rate (cm/year)		
		Minimal	Maximal	Mean (stdev)
I	3	0.60	1.23	0.82 (0.35)
II	7	0.26	2.20	0.90 (0.69)
III	4	0.48	2.00	1.27 (0.62)
IV	3	0.56	1.43	1.07 (0.46)

Table 3: Distribution of erosion patterns based on lithology of sub-soil.

Erosion pattern	I	II	III	IV
Number of trees	3	7	4	3
Volcanic rocks	1	-	3	-
Loess	2	7	1	3

cross sections) were exposed from the volcanic bedrock and 13 trees from loess. Erosion patterns **II** and **IV** occur only in loess. The dominant erosion pattern in the volcanic bedrock is pattern **III** (Table 3). The mean erosion rate in volcanic rocks is 1.26 cm/year, whereas the mean erosion rate in loess is 0.92 cm/year. However, both values are not statistically significantly different (p -value from t -test = 0.15).

5 Discussion

52 root samples coming from 16 exclusively broad-leaved trees (ring porous and diffuse porous) were used for reconstruction of gully side erosion close to Kozárovce village. Dendrogeomorphic analysis enabled reconstruction of a 41 year chronology of erosion processes (AD 1972 – 2013) and discovered 23 event years.

Dendrogeomorphic studies of erosion processes usually use anatomical analysis of coniferous species [14, 40, 41]. This preference comes from the quite clear visible anatomical reaction of tree roots on exposure. The moment of exposure is even more clearly visible on the microsections of root samples. Nevertheless, analysis of broad-leaved trees for erosion studies is becoming more widespread in dendrogeomorphic research [37, 39]. Identification of exposure moment in the tree-ring series is not as easy as in the case of coniferous trees; nevertheless, modern approaches based on microscopic analysis of anatomical features bring good results. We used identification of macroscopically visible signals from prepared root samples surfaces. As the anatomical reactions were not always

well visible without microsection analysis we focused on root eccentricity, scars and colour changes which can be interpreted as results of root exposure. Next, growth response to exposure in the root-ring series can be adenoidal or not clear in the case of horizontally growing roots. Material moving from upper part of slope can bury the root upside and can stop growth reaction in this part of root [9]. To prevent this effect, only roots growing in a (sub)vertical position were sampled. Another potential source of uncertainty can play a role when morphological changes start to occur even before the real root exposure [32]. The time of root exposed growth would be longer in these cases. From this point of view, the reconstructed E_R values could be considered as minimal. Recently, other uncertainties regarding tree roots exposure data using in erosion studies were pointed out [see *e.g.* 42].

The values of erosion rates (mean $E_R = 1.00$ cm/year) are quite high in comparison with results of other authors obtained by dendrogeomorphic methods. Comparable results are obtained *e.g.* [43] from roadcut environment (1.00–1.10 cm/year). Higher values of the slope erosion rate are rather rare, *e.g.* [40] reconstructed lake shore erosion with values of 2.80–9.20 cm/year or [44] sea shore erosion with values of 2.20–2.60 cm/year. Most of the dendrogeomorphically reconstructed values of erosion rates from different environments are lower. Generally, a low erosion rate is determined in hillslope environment. For example [45] reconstructed erosion rate Iran with value of 0.05 cm/year, [46] in USA values of 0.20–0.30 cm/year, [47] in USA value of 0.03 cm/year or [33] in Spain value of 0.16–0.26 cm/year or [32] the value of 0.62–0.88 cm/year. If we look on reconstructed erosion rates just in gullies of middle Europe, very high values of gully retreat rate were obtained *e.g.* [48] in southern Poland (63 cm/year), or [49] in the east of the Czech republic even 319 cm/year. However it must be noted that these values express the rate of gully retreatment (not deepening or widening).

It is necessary at this point to note some next potential aspects influencing the values of reconstructed erosion rates. The upper parts of slopes, which are covered by loess material, are potentially unstable particularly if

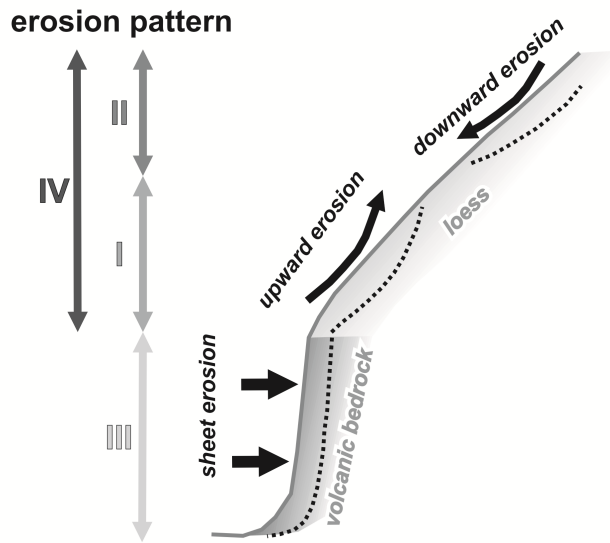


Figure 8: Model of the gully side development.

they are weighted by trees. In some cases the trees, growing on the edge of gully slopes, move downslope due to combination of gravity and unstable subsoil. During slow stem movement the roots growing downslope can be shovelled; in some cases the maximal distance of root from the soil surface can be overestimated. This effect could potentially explain some high values of erosion rate. To be sure about really precise dates of root exposure, it is very suitable (if not necessary) to realize anatomical analysis of roots structure. Nevertheless, due to quite wide root rings (often more than 5 mm), some anatomical features (particularly changes in the vessel size) were visible even under binocular microscope without microsection preparation. In spite of this, some inaccuracy in exposure dating can occur if only macroscopic identification of root exposure is used.

Based on the chronology of individual parts of single roots exposure the patterns of gully side development were created. Reconstructed erosion patterns represent a unique view on the side and the whole gully cross profile development. The local model of slope development is presented in Figure 8. It can be seen that the lower part of gully sides develop preferably by sheet erosion (parallel slope retreat). These parts of the side are exclusively incised into volcanic bedrock. Lithology of the side probably influences the character of side erosion in these positions. On the very steep slopes falling of small volcanic rock blocks is visible. Subsequent root exposure is very fast; that is why the anatomical signals in root-rings were well visible [9]. Fast side development is confirmed by the erosion rate values (pattern III; Table 3). Erosion is proba-

bly not continuous, and long period with no signs of development can be observed. For this reason, the values of erosion rate from these positions must be considered as really average for long period [18]. On the other hand, erosion in upper part of sides can be due to loess subsoil considered as more continuous (*i.e.*, higher frequency of partial erosion events; not classical continuous erosion). Moreover, identified and dated root reactions (abrupt changes of the tree-ring width) are considered as evidences of rather moderate magnitude-frequency erosion activity [see 38]. Unconsolidated material probably better react on rainfall triggers and erosion events have higher frequency than in the case of lower part of sides in volcanic rocks. Upper parts of slopes develop preferably due to a combination of upward and downward erosion. The downward erosion was distinguished almost exclusively in the highest parts of sides. The upward erosion could be initiated by undercutting of lower loess border due to parallel retreat of underlying volcanic rocks. The dated “events” are dates of roots exposures. As mentioned above, due to the type of growth reactions, roots exposures can be considered as abrupt. In this context, the probable triggering factors are extreme hydrometeorological events, which have different geomorphic effect in parts of sides created by different lithology. Unfortunately, detailed precipitation data in appropriate resolution and distance from study site were not available. Nevertheless, the triggers of erosion events can be expected to be high-magnitude short-duration precipitation events.

The reconstructed model of gully side development is preferentially applicable for the studied gully or the gullies in its wider surrounding. Nevertheless, it could potentially be valid in the other regions of the world with similar environmental (geomorphic, lithological, meteorological and vegetation) conditions. As the part of catchment above the upper border of studied gully is used as arable land, data about side gully development are important from a landuse management and potential protection of land resources point of view.

6 Conclusion

Erosion is dangerous geomorphic process and its study is of high importance. Dendrogeomorphic methods were used in a slope erosion study in a ~220 m long gully close to Kozárovce village. Analysis of 52 root samples from 16 trees enabled reconstruction of 23 erosion event years.

We tried to identify the moment of root exposure based on macroscopic analysis of prepared root surfaces. Never-

theless, we must conclude that microscopic analysis of microsections would surely help to verify the dating and for future research of used tree species we recommend it.

We reconstructed several erosion patterns on sides and were able to build a local model of gully side development for the studied area. Based on the model, we were able to explain the development of current gully cross profile. We see a clear dependence of erosion pattern on the lithology of subsoil.

The reconstructed erosion rates are relatively high in comparison to studies from similar or different environments across the world. In some cases, high values of erosion rates can potentially be explained by gravitational moving of trees and subsequent deformation of downward roots. That is why we call for detailed and very precise mapping of sampled tree roots surroundings. The anatomical analysis of roots is very suitable in this case.

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