STUDIA GEOMORPHOLOGICA CARPATHO-BALCANICA

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DENDROGEOMORPHOLOGICAL ANALYSIS OF A HEADWATER AREA IN THE GORCE MOUNTAINS

Abstract. There are a number of steep forest-covered headwater catchments in the Gorce Mountains — a flysch-type range that is part of the Polish Carpathian Mountains. The range exhibits fresh signs of contemporary geomorphic activity. The erosional landforms such as torrential channels, ravines, rills and rock veneer occurred within headwater areas — were selected for detailed geomorphological mapping. Select landforms were inspected for the presence of exposed roots with particular attention paid to scarred exposed roots. Microanalysis of 42 roots, was performed based on the procedure by F.H. Schweingruber (1990), Gärtner et al. (2001). Analytical data were compared to available rainfall data collected by meteorological stations located in close proximity to the study area (Turbacz and Rabka stations). It has been determined that the roots had become exposed at different times ranging anywhere from 1944 to 2007. Wood anatomy changes plus detailed geomorphological mapping enables to reconstruct spatial and temporal patterns of erosional processes within headwater areas. Furthermore, on the base of roots analysis the volume of sediment removed during particular event was estimated. Data obtained from such analysis yields insight into the role of different rainfall events in the development of headwater areas in middle mountains.

Key words: headwater area, dendrogeomorphological analysis, exposed roots

INTRODUCTION

A headwater area is a well-established concave landform that is part of a complex morphodynamic subsystem of middle mountain catchments. It is found on the boundary line between two subsystems: a slope subsystem and a fluvial subsystem (Montgomery and Buffington 1997). Its development, as described by M. Baumgart-Kotarba (1974), takes place in the form of impulses driven by surface and linear processes. Headwater areas are characterized by the diverse dynamics of a number of underlying processes. Their most active parts are V-shaped valleys, ravines, logging roads, hollows, rock veneers, creep zones and landslide surfaces.

The development of particular meso- and micro-landforms is associated with the activity of different natural and anthropogenic processes such as deep erosion, reverse erosion, sheet erosion, piping, landslides, settling, creeping, erosion associated with the overturning of trees, as well as logging activity (Wrońska 2006). The combined action of these processes drives the development tendencies of particular headwater areas. In heavily wooded areas, such processes are associated with the exposure of tree roots.

The internal structure of exposed roots changes in response to different temperatures and levels of humidity. Exposed roots affected by altered temperatures and humidity levels are a potentially valuable source of information on the temporal and spatial variability of particular geomorphological processes.

Dendrochronological and dendrogeomorphological analyses have been performed, first of all, in loess areas and have addressed primarily the subject of gully erosion (Vandekerckhove et al. 2001; Malik 2006). There are relatively few publications on the subject of erosion analysis based on anatomical changes in tree roots in flysch areas where eroded landforms are found in different types of slope cover (Buchwał 2008; Buchwał and Wrońska-Wałach 2008).

The dendrogeomorphological method can be used in the analysis of different types of geomorphological processes. It has been used to analyze rockslides, landslides, rockfalls, snow avalanches, rock avalanches, and erosional processes. However, most existing research studies have been based on stem ring analysis (Alestalo 1971; Carrara and Carroll 1979; Strunk 1997; Stoffel 2006; Bollschweiler et al. 2007; Pelfini and Santilli 2008; Stoffel and Bollschweiler 2008; Zielonka et al. 2008).

In recent years, changes in wood cell anatomy caused by slow or sudden exposure to changing temperatures and humidity levels have gained recognition as a useful tool in geomorphology (Gärtner et al. 2001; Gärtner 2003, 2006).

Measurements of gradual changes in wood cell anatomy are used to assess surface soil erosion levels (Bodoque et al. 2005; Perez-Rodriques et al. 2007; Rubiales et al. 2008; Buchwał 2008). Furthermore, changes in the size of wood cells in roots of different species of trees are used to reconstruct the frequency and magnitude of extreme phenomena acting in different types of natural environments (Malik 2008; Malik and Matyja 2008; Hitz et al. 2008).

Still, there is a relative dearth of information on the subject of the application of dendrogeomorphological analysis to the identification and assessment of the role of erosional processes in the shaping of headwater areas in middle mountains. Data obtained using this type of method can help to better understand the role of surface erosion processes, linear erosion, piping, landslides, and torrential runoff in the shaping of headwater areas.

The purpose of this paper is to present an assessment of the possibilities available to researchers who choose to use the dendrogeomorphological method in the analysis of geomorphological processes affecting headwater areas. The paper includes measurements of anatomical changes in roots of trees exposed by the action of external factors. An attempt has also been made to estimate the volume of material removed from each landform of interest during a selected period of time. In addition, the paper attempts to compare tree exposure periods with available precipitation data for corresponding periods of time. Geomorphological landforms were selected in a manner that affords a representative sample of typical natural scenarios affecting headwater areas.

STUDY AREA

The research was conducted in the Gorce Mountains, a mountain range built of a flysch lithostratigraphic unit called Magura nappe. With an elevation of 1,200–1,300 m a.s.l. and a slope gradient of more than 20°, they are representative of middle mountains (K l i m a s z e w k i 1972).

The study area is located within the Gorce National Park on the southern edge of the Gorce Mountains and features a number of steep forest-covered headwater catchments (Fig. 1). The headwaters in this area exhibit fresh signs of contemporary geomorphological activity. The first landform studied is located in the upper part of the Olszowy Stream headwater area.

Test areas for dendrogeomorphological analysis were selected within the Olszowy Stream headwater area. The spring is located on the northwestern slope of Turbacz Ridge (1,311 m a.s.l.) and represents a typical headwater area formed in the middle of a landslide. It consists of a 20–50 m niche (30–45°), landslide packets, and an expansive landslide tongue. The headwater area has a surface

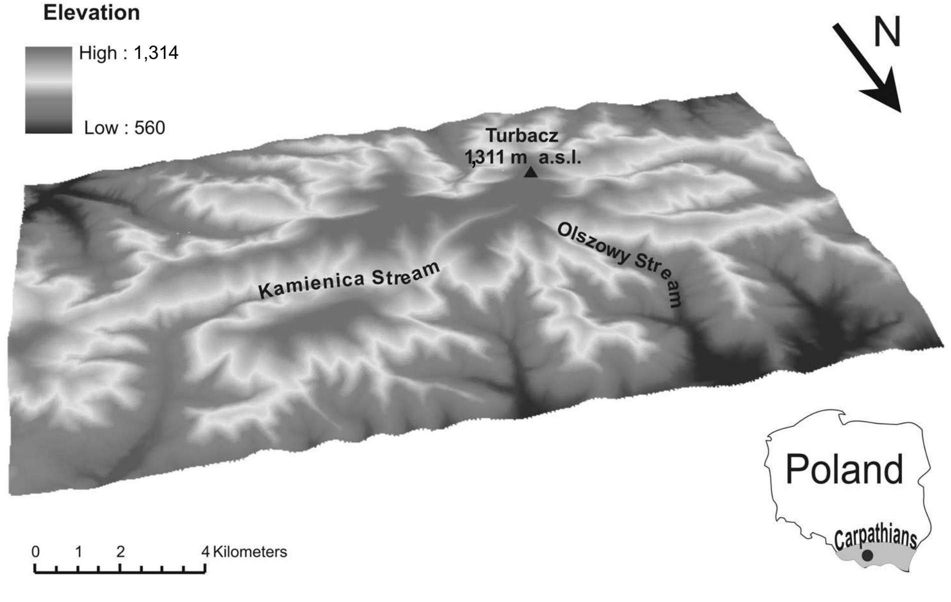

Fig. 1. Location of study area

area of 0.62 km^2, density of 7.03 $km \cdot km^{-2}$, and an average gradient of 25–30°. The part of the headwater area featuring the strongest landform diversity is the top part. Erosion-induced rills, ravine-type valleys, rock veneers, torrential channel, and small secondary landslides can all be found in this part of the headwater area.

The surface of the headwater area is covered with mature subalpine spruce forest (Chwistek 2001). Spruce density (*Picea abies*) is quite uniform throughout the headwater area and ranges from 7.1 to 8.0 trees per 100 m^2 (Loch et al. 2001). Climate conditions in the Gorce Mountains are characterized by the existence of several climate zones. Average annual air temperature varies along the mountains' longitudinal profile from 6–7°C at the foot of the range to 3°C along the ridges (Hess 1965). Average total annual precipitation ranges from 750 to 800 mm at lower elevations to 1,200 mm on Turbacz Ridge. Precipitation maxima occur in July and August.

RESEARCH METHODS

Selected headwater area in the Gorce Mountains were subjected to detailed geomorphological mapping. Landforms that were deemed to be the most typical for the upper parts of headwater areas, and were appreciably different in terms of relief, were selected for further analysis. Next, selected landforms such as a torrential channel as well as a rock veneer along with a nascent ravine and adjacent slope were subjected to detailed inspection for the presence of exposed spruce (*Picea abies* (L.) Karst.) roots.

GPS technology — Garmin 60 CSx and Kestrel 4000 with a built in altimeter — was used to accurately document the locations of selected roots. Landforms featuring exposed roots were subjected to further analysis including measurements of length, width, and depth. In the case of larger eroded landforms, a longitudinal field profile was produced, noting the type of material forming each step of the landform.

The geomorphological maps produced were used to draw initial conclusions about the processes that may have shaped each landform of interest. In addition, perpendicular profiles were produced every 20 m for each mapped landform. Special attention was paid to gradient change zones and changes in valley width.

The exact location of each root was mapped within each geomorphological landform of interest. Samples were collected from the bottom and the sides of selected landforms. In the case of eroded landforms no. 1 and 2, samples were obtained from roots growing across the landforms. Altogether, 46 root disks were collected. Samples were collected at least one meter away from tree stem in order to avoid distortions caused by mechanical factors associated with stem stabilization. Four of the collected roots were found to be not suitable for further analysis. Two of the roots had a destroyed core while the other two were dead. As a result, only 42 out of 46 roots were used in further analytical work.

All the collected root disks were polished and prepared for macroscopic analysis, the result of which was the identification of the most significant annual change zones and the locations of erosional scars. Samples were then prepared for microscopic analysis. Rectangular fragments were cut out of disks along their diameter, considering the fact that roots tend to have wedging rings and false rings. The fragments obtained in this manner were as complete as they could be in terms of annual growth rings. Each fragment was then softened in distilled water.

A Microtom "GSL 1" was used to cut 15–20 μm samples out of the prepared wood fragments for microscopic analysis. The microscope samples were processed according to a procedure developed by F. Schweingruber (1990). Each sample was stained using a 1% Saffron/Astra Blue solution, dehydrated, washed with ethyl alcohol and xylene in order to remove excess stains, and finally affixed to a microscope slide using a synthetic resin called Canadian Balsam. Microscope images were produced using each prepared slide.

Changes in the anatomy of the roots selected were identified in order to reconstruct the geomorphological processes that had acted upon each headwater area of interest. Particular attention was paid to anatomical changes in early wood. Early wood cell size was calculated (EW = early wood) based on consecutive annual growth using a manual graphing program called ImageJ. Changes in cell size ranging from 50% to 60% are considered a sign of root exposure and response to changing temperatures and humidity levels (Gärtner et al. 2001; Gärtner 2003).

Special attention was paid to the location of erosional scars and the density of traumatic resin ducts (TRDs). Both features were compared to changes observed in early wood. Erosional scars provide additional information on the course of geomorphological processes. F. Schweingruber (1990) has suggested that they are the product of cambium damage caused by rock debris transported by water. The presence of such scars, therefore, can help identify the geomorphological processes that may have led to the formation of a given landform.

Detailed plans such as longitudinal profiles and perpendicular profiles were produced in the field. The height of undercuts was measured along the entire length of the torrential channel. This measurement along with the measurement of the width of the incision at locations that differed in terms of structure, as well as root dating were used to estimate the quantity of material that had been eroded away during subsequent hydrological and geomorphological events.

The dates obtained for roots exposed as a result of the action of external factors were compared to available precipitation data collected by weather stations on Turbacz and Rabka. The Turbacz Station is the weather station closest to the study area (700–800 m away). The station's precipitation data cover the 1956–

1981 time period. In order to supplement the Turbacz data range, precipitation data were also obtained from the weather station in Rabka. The Rabka Station is located about 10 km away from the study area and covers the 1955–2007 time period. The correlation coefficient for the precipitation data sets from the two stations is $r = 0.86$, which is statistically significant. The following two types of precipitation data were used in the research study: monthly totals from June to August and daily maxima.

RESULTS

Dendrogeomorphological analysis of the samples collected indicates a wide range of spruce root (*Picea abies* (L.) Karst.) exposure dates from 1944 to 2006 (Tab. 1). The largest number of roots had become exposed from 1984 to 1987 (41.5%) and from 1967 to 1972 (26.8%). Each eroded landform tends to have a different range of root exposure dates. Landform no. 2 (Tab. 1, Fig. 3) has been

Table 1

Root sample characteristics

Sample no.	Exposure [year]	Landforms – sampling sites
O-1	1985	ravine
O-2	1991	ravine
O-3	1944	ravine
O-4	1997	ravine
O-5	1970	ravine
O-8/3	1984	rock veneer
O-12/3	1981	rock veneer
O-13	1953	rock veneer
O-14	1971	rock veneer
O-15	1968	rock veneer
O-16	1985	rock veneer
O-17	1985	rock veneer
O-18	1987	rock veneer
O-20	1979	rock veneer
O-21	1987	rock veneer
O-22	1979	rock veneer
O-23	1985	rock veneer
O-24	1970	rock veneer
O-28	1967	slope
O-29/II	1985	slope

Table 1 cont.

Sample no.	Exposure [year]	Landforms – sampling sites
O-30	1985	slope
O-31-1	1980	slope
O-31-2	1986	slope
O-32-1	1979	slope
O-32-2	1994	slope
O-69	1985/86	rill
O-70	1971	rill
O-71	1988	rill
O-72	1985	rill
O-73	1985	rill
O-74	1989	rill
O-75	1987?	torrential channel
O-76	1970	torrential channel
O-77	1971	torrential channel
O-78	1971	torrential channel
O-79	1986?	torrential channel
O-80	1987	torrential channel
O-81	1984	torrential channel
O-82	1973	torrential channel
O-83	1971	torrential channel
O-84	1995	torrential channel

shown to possess the widest root exposure date range. Anatomical changes point to sudden (one time) exposure 41.5% of the time and gradual exposure 58.5% of the time. One time changes in root cell anatomy have been shown to occur every 10–12 years. Each landform in question has experienced at least two geomorphological events.

Eroded landform no. 1 is located in the upper part of the Olszowy Stream headwater area. It starts at an elevation of 1,220 m at the edge of a landslide niche. It is a 115 m long torrential channel and consists of steps along its longitudinal profile. The steps are usually part of spruce root and rock debris structures. The landform ends in the form of a torrential fan at the ceiling of a landslide packet (Fig. 2).

The maximum width of landform no. 1 is 2.5 m while its depth is 1.0 meter, on average, and does not exceed 1.4 m. Anatomical changes in the roots indicate a one time sudden exposure (Fig. 4). Roots collected at this site had become exposed in two stages. Samples collected from the upper section of landform no.

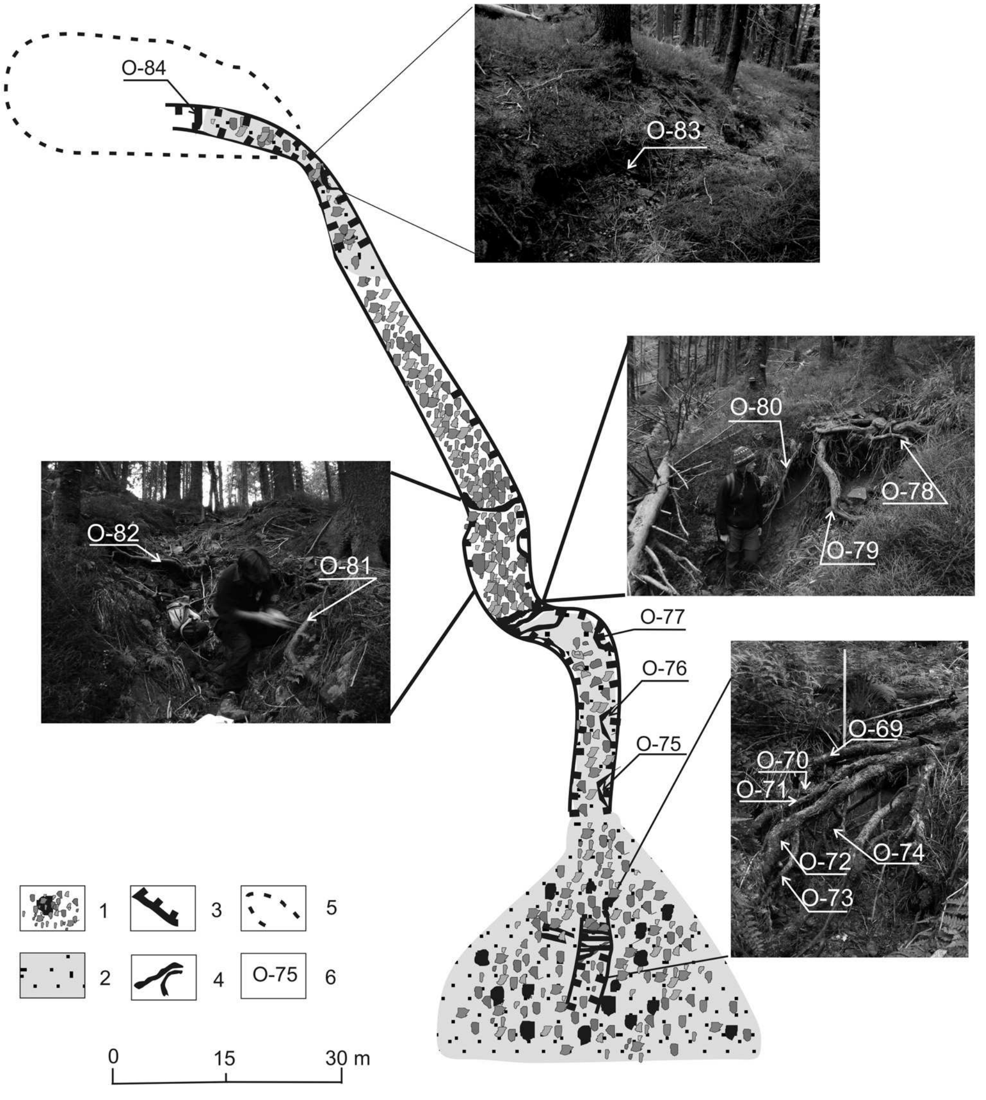

Fig. 2. Geomorphological outline of landform no. 1; 1 — large rock debris, 2 — fine rock debris, 3 — torrential and rill edges, 4 — exposed root samples, 5 — slope trough, 6 — number of samples (see Tab. 1)

1 and the steps on roots found along the torrential channel had become exposed from 1970 to 1972. They can be found along with roots, which had become exposed (5 samples) or damaged (9 samples) in 1985 and 1986 at the end of the growing season. Roots exposed in 1985 can be found in the lower part of the torrential channel and in the central part of the torrential fan.

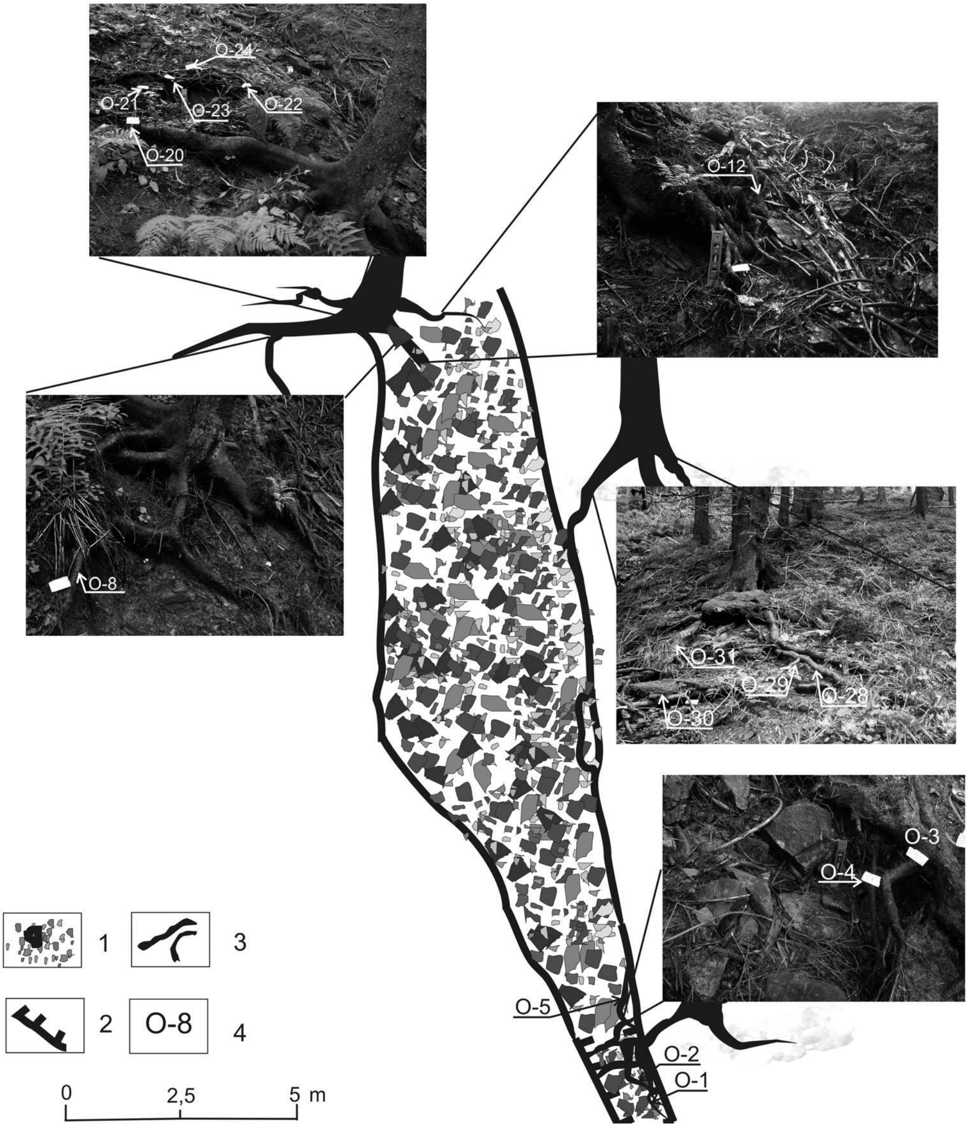

Fig. 3. Outline of landform no. 2, 1 — large and fine rock debris, 2 — ravine edges, 3 — exposed root samples, 4 — number of samples (see Tab. 1)

The central part of the fan is split by an erosional rill spanned by roots (Fig. 2). All roots analyzed for this site have signs of damage in the form of erosional scars. Both geomorphological mapping and root sample analysis for landform no. 1 indicate that this landform had been cut directly into a slope surface and is the result of extreme geomorphological events, which had taken place during the summer months from 1970 to 1972.

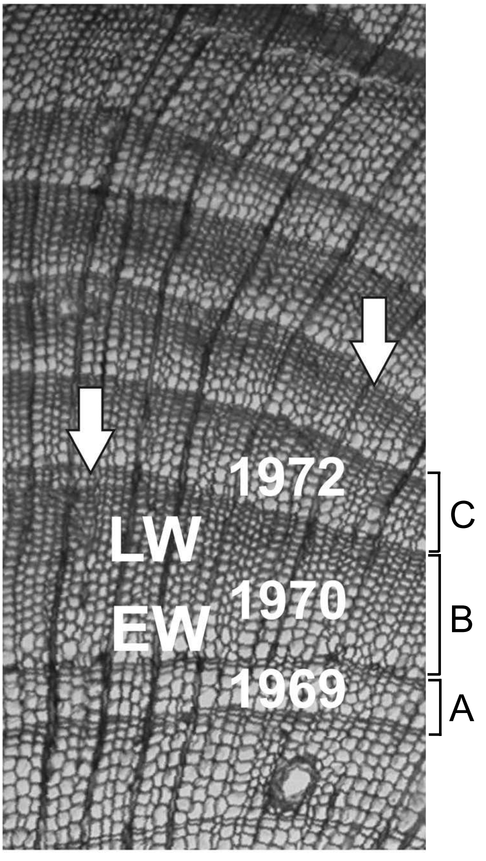

Fig. 4. Example of a cross-section of a root exposed abruptly to the action of external factors. A — annual growth characteristic of roots before exposure, B — annual growth characteristic of roots following exposure towards the end of the growing season, C — annual growth characteristic of roots following exposure (changes in EW occur starting at the beginning of the growth period), white arrows — indicate wedging rings

Landform no. 1 had undergone only minor modifications from 1985–1986. This type of situation creates favorable conditions for the estimation of the volume of material transferred off the slope surface in the headwater area during extreme geomorphological events. The 115 m long landform had lost 108.8 m^3 of mineral material from 1970 to 1972.

Eroded landform no. 2 is located in the upper part of the Olszowy Stream headwater area — about 35 m west of eroded landform no. 1. It is a rock veneer along with an adjacent slope and a small nascent ravine (Fig. 3). In this case, roots had become exposed from 1944 to 1997. Analysis of anatomical changes in roots indicates gradual exposure to external factors. The root exposures can be grouped into defined time periods. The largest number of roots had become exposed from 1984 to 1987 (40%). Twenty percent of roots had become exposed from 1979 to 1981 while another twenty percent from 1967 to 1971. The root located in the central part of the nascent ravine had become exposed in 1944.

The ravine also contained the root (O-4) that had become exposed most recently (1997). A root (O-5) located in the upper part of the ravine near the edge of the rock veneer, hanging at an average height of 15.2 cm, features anatomical changes that indicate a one time sudden exposure (Fig. 6) in 1970/1971.

Roots obtained from the lower part of landform no. 2 possessed changes in their early and late wood cell structure that indicate gradual exposure. A 50–60% reduction in early wood cell size indicates a final exposure in 1985 and 1991 (Fig. 5). A root located parallel to the landform at an average height of 14.7 cm had become exposed gradually with final exposure in 1997. On the other hand, a root hanging 34.2 cm above the floor of the nascent ravine possessed anatom-

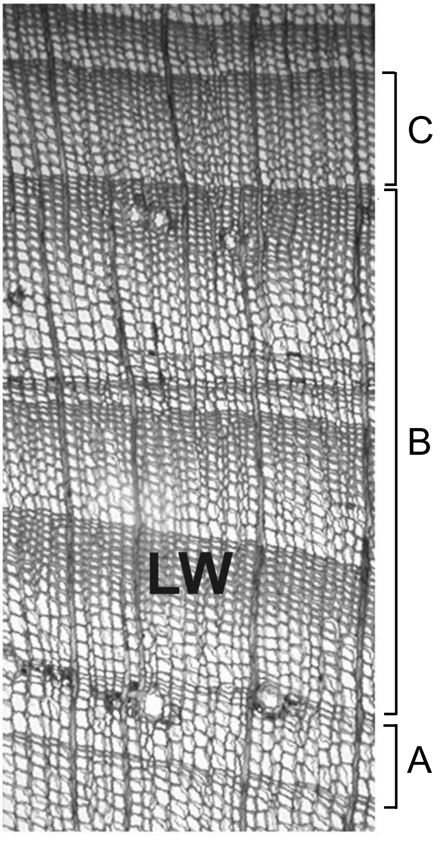

Fig. 5. Example of a cross-section of a root exposed continuously to the action of external factors. A — typical annual growth in root, B — annual growth characteristic of roots exposed gradually. A characteristic trait is the presence of numerous late wood cells (LW), C — growth in tree ring following root exposure

ical changes in its early wood growth dating back to 1944. Roots collected from the rock veneer had become exposed from 1953 to 1987 with 69% having become exposed from 1979 to 1987. Finally, roots collected from the slope had become exposed from 1967 to 1994 with 71% having become exposed from 1979 to 1986.

A large number of exposed roots within a small area allows for the estimation of average surface erosion. The rate of average erosion was determined using H. Gärtner's Equation (2007):

$$E_{ra} = E_r / NR_{ex}$$

where:
E_{ra} is the average erosion rate (mm/year),
E_r is the height at which a root is suspended over a surface or another root,
NR_{ex} is the number of annual growth rings in a root since the date of exposure until today or the age of another root — the difference between the date of root sampling and the date of its exposure.

The average erosion rate was calculated for all sampled roots (Fig. 6). The largest average values were determined for root O-16 (13.9 mm/year), located in the rock veneer, as well as for roots O-2 and O-4 (12.3 mm/year), located in the nascent ravine. The smallest average value was determined for root O-28

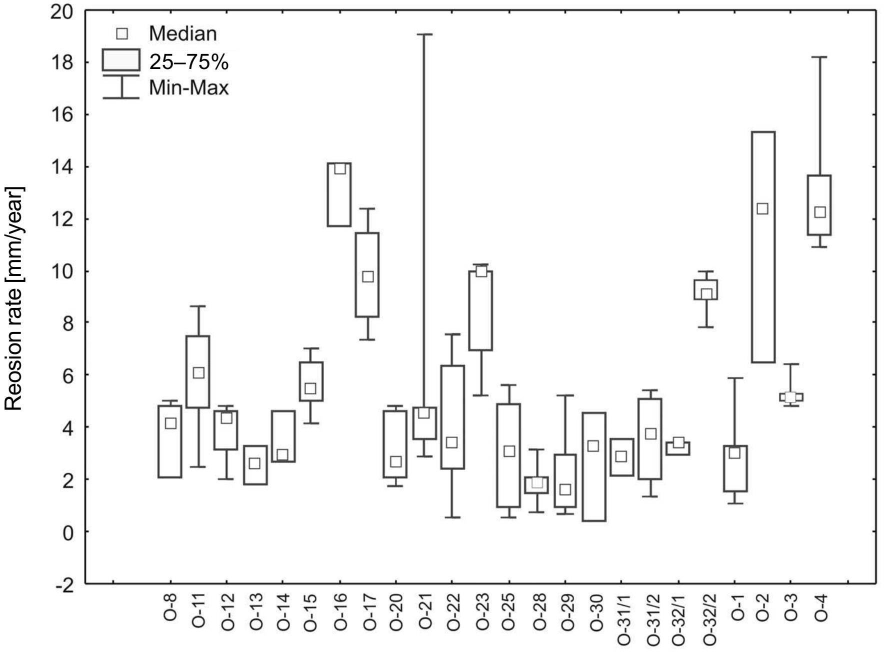

Fig. 6. Comparison of erosion rate for individual roots located across the rock veneer, slope, and ravine, O-2 — root numbers (see Tab. 1)

(1.9 mm/year), collected from the slope adjacent to the rock veneer. Maximum erosion rate values were determined for root O-21 (19 mm/year), found in the rock veneer, and root O-4 (18.2 mm/year), found in the ravine. Minimum erosion rate (below 1 mm/year) were determined for roots O-22 and O-25, found in the rock veneer, as well as for roots O-28, O-29, and O-30, found on the slope.

There exists a clear relationship between root exposure dates and available precipitation data. Maximum daily precipitation values are clearly correlated with root exposure periods for the torrential channel as well as for individual roots exposed in the rock veneer (Fig. 7). High precipitation values correspond to root exposure in 1958, 1968, 1970, 1972, 1979, and 1981. The studied landforms also contain numerous roots that had become exposed from 1984 to 1987 — a period with no recorded high precipitation values.

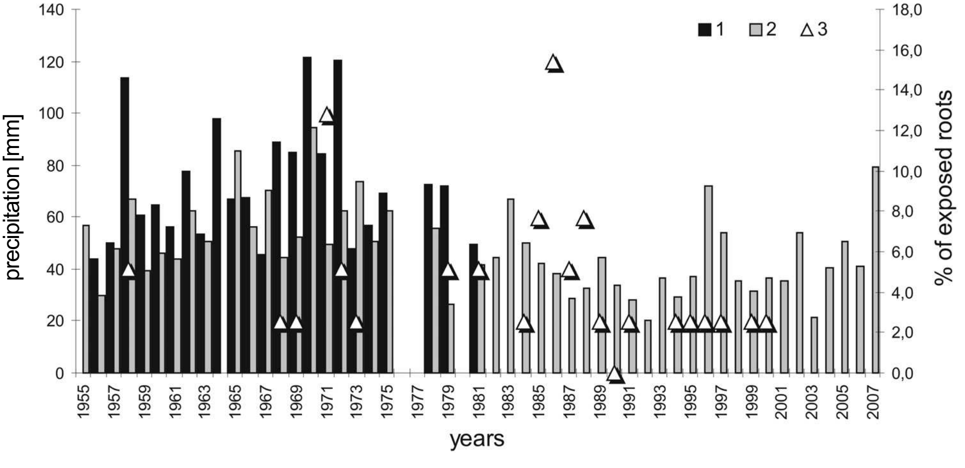

Fig. 7. Comparison of precipitation with % of exposed roots: 1 — maximum 24-h precipitation recorded at Rabka meteorological station (1955–2007), 2 — maximum 24-h precipitation recorded at Turbacz meteorological station (1956–1981), 3 — % of exposed roots collected from upper part of headwater area

DISCUSSION

Headwater areas are affected by a variety of geomorphological processes. They are the product of processes that occur at various points in time and with different levels of intensity. Dendrogeomorphological analysis can help lead to a better understanding of the functioning of different parts of headwater areas. Given a large enough number of similar landforms, the relationship between headwater area features such as gradient, soil or rock cover, forest density, forest age, and geomorphological process dynamics can be determined.

The research presented herein was based on the most typical of geomorphological headwater area landforms. The landforms in question were selected based on their ability to provide contrasting field scenarios. H. Gärtner et al. (2001) had identified the possibility of differentiating roots exposed to external factors one time and those exposed gradually. This type of approach allows for the identification of geomorphological landforms produced by extreme hydrological and geomorphological events and those produced by slow erosional processes.

Root exposure periods can be compared to precipitation data collected by nearby weather stations. I. Malik (2006) pointed out the problem of correlating precipitation data with erosion episodes resulting from the occurrence of highly localized storm cells, which may be out of range for some weather stations. In the case of headwater areas, this problem may distort correlations with precipitation data. T. Gomi et al. (2002) pointed to the high frequency of isolated localized downpours and their relationship to headwater areas. Analysis of roots collected from the torrential channel indicate a relationship between root exposure dates and years (1958, 1968, 1970, 1971) characterized by high precipitation levels (Fig. 4).

There are also years such as 1984, 1985, and 1986, when root exposure and scarring were quite common, both in the torrential channel and in the rock veneer, which do not correlate with precipitation data. The reason for this may be the distance (10 km) of the weather station from the research site. However, the sheer number of root exposures identified cannot be accidental and may, therefore, be helpful in the identification of areas of high precipitation located away from weather stations. In the case of roots that had experienced a sudden (one time) exposure, the landform where they had been found must be the product of an extreme geomorphological event.

Another possibility afforded by dendrogeomorphological analysis is the estimation of the quantity of material transported through a headwater area during a given amount of time. L. Vandekerckhove et al. (2001) analyzed various attempts designed to estimate the volume of material removed as a result of gully erosion. The researchers classified field scenarios based on the timing of an erosion event and the age of the tree of interest. They concluded that if an erosion event is younger than the age of the tree or a part of it, then it is possible to overestimate the volume of material removed.

However, if the tree of interest is the direct result of an erosion event, then the probability of correctly estimating the volume of material removed is the greatest. The third scenario is when a tree is younger than the erosion event of interest; in this case, it is possible to underestimate the volume of material removed. The second scenario is the one that is reflected by the analysis of anatomical changes in root wood exposed to external factors. Changes in roots are a direct consequence of the action of geomorphological processes. If it can be assumed that the first mark on roots points to a first stage of development or renewal of an older geomorphological landform, then it should be possible to estimate the amount of mineral material removed from the landform either during the event of interest or since the moment of first root exposure until today.

A sample analysis of the erosion rate for a variety of geomorphological landforms illustrates the possibility of using the dendrogeomorphological method in spatial research on the differences in the activity level of erosional processes. Statistically significant differences (Fig. 8) can be observed between average values of the erosion rate estimated for three different landforms.

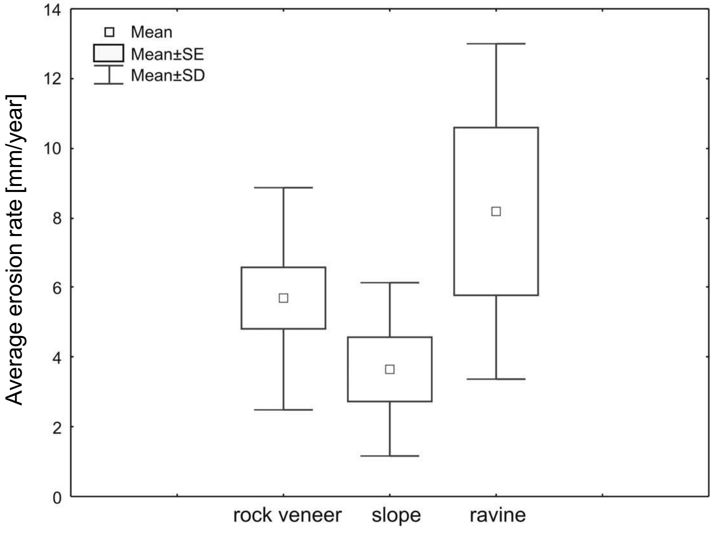

Fig. 8. Comparison of average erosion rate [mm/year] for three landforms: rock veneer, slope, and nascent ravine

The highest average erosion rate (8.1 mm/year) was calculated for the nascent ravine-type valley located below the rock veneer. A somewhat lower value (5.1 mm/year) was calculated for the rock veneer. The lowest value of the erosion rate (3.4 mm/year) was calculated for the slope adjacent to the rock veneer. The widest spectrum of average erosion rates was determined for the ravine (s = 4.82). Average erosion rates varied somewhat across the rock veneer (s = 3.2) while those calculated for the slope were found to be quite similar (s = 2.4).

The analysis of erosional processes in headwater areas is not a simple matter and neither is the estimation of the volume of material removed. This type of analysis requires highly accurate geomorphological mapping that leads to a proper choice of root sampling sites. Dendrogeomorphological analysis also assumes that a certain amount of lag time has been considered. In this case, lag time refers to the amount of delay in the response of a root to a particular exposure event. I. Malik (2006) emphasized the importance of this issue. Root response largely depends on the particular point in time during the growing season when a root becomes exposed. If root exposure takes place from May to the beginning of August, then anatomical changes will already be visible during the same period of annual growth.

If, however, an event occurs towards the end of the growing season or during a period free of cambium activity, then changes will be visible during the following annual growth period (Fig. 4). This type of analysis is also hindered by a certain type of error that makes it difficult to estimate the erosion rate and the morphological effectiveness of a given geomorphological event in a simple manner. There are three sources of error: commonly occurring in roots growth rings that wedging (Fig. 4 — white arrows), false rings, and the measurement method itself. This leads to a root exposure measurement accuracy of ± 1 or two years.

For this very reason, root exposures noted for the torrential channel from 1970 to 1972 may refer to a single event, which had taken place between 1970 and 1972. In such a case, the estimated volume of transported material (108.8 m^3) may pertain to a single precipitation event, which had formed the torrential channel. The grouping of root exposure dates from 1970 to 1972 may also be the result of so-called clustering processes, described extensively by L. Starkel (1996, 2002). A clustering process is understood as a specific situation where morphologically active geomorphological events take place year after year. Such a process could have occurred during the research period, given the maximum daily precipitation values recorded at the Turbacz weather station in 1970, 1971 and 1972 (121.6, 84.4 and 120.4 mm, respectively).

CONCLUSIONS

Dendrogeomorphological analysis helps to distinguish zones within headwater areas affected by different types of morphological processes. Each type of dendrogeomorphological analysis requires an individual approach. The accurate determination of the location of roots within a selected area is very important. Single samples exposed at different locations only allow for the determination of material removed during a particular erosion event in the immediate vicinity of a given root. In order to perform a more complete estimation of the volume of material removed, roots that span the landform of interest must be analyzed.

Given a large enough number of root samples collected from several parts of the geomorphological landform of interest, it is possible not only to reconstruct the rate of formation of a given landform but also to estimate the quantity of material removed during a particular time interval. Finally, it is also possible to determine precipitation thresholds that trigger different types of morphometric processes in different parts of headwater areas.

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