

ROMANIAN ASSOCIATION OF GEOMORPHOLOGISTS

REVISTA DE GEOMORFOLOGIE

24(2)



editura universității din bucurești®
2022

Revista de Geomorfologie 24(2)/2022

Editor-in-Chief:

Maria Rădoane, University of Suceava, Romania

Guest Editors:

David R. Butler, Texas State University, United States of America

Mircea Voiculescu, West University of Timișoara, Romania

Editorial Board:

Achim Beylich, Geological Survey of Norway

Armelle Decaulne, Université de Nantes, France

Aurel Perșoiu, Institute of Speology Emil Racovita, Romania

Ciprian Mărgărint, Al I Cuza University of Iași, Romania

Dan Dumitriu, Al I Cuza University of Iași, Romania

Daniel Germain, Université du Québec à Montréal, Canada

Dănuț Petrea, Babeș Bolyai University of Cluj-Napoca, Romania

Floare Grecu, University of Bucharest, Romania

Florin Pendea, Lakehead University, Orillia, Canada

Florin Tătui, University of Bucharest, Romania

Hans-Balder Havenith, Université de Liège, Belgium

Ian Evans, Durham University, United Kingdom

Jean-Philippe Malet, Université de Strasbourg, France

Laura Comănescu, University of Bucharest, Romania

Lucian Drăguț, West University of Timișoara, Romania

Marta Jurchescu, Institute of Geography, Romania

Mauro Soldati, Università degli Studi di Modena e Reggio Emilia, Italy

Mihai Micu, Institute of Geography, Romania

Mihai Niculiță, Al I Cuza University of Iași, Romania

Mircea Voiculescu, West University of Timișoara, Romania

Nicolae Cruceru, Institute of Speleology Emil Racovita, Romania

Olimpiu Pop, Babeș Bolyai University of Cluj-Napoca, Romania

Paola Reichenbach, Istituto di Ricerca per la Protezione Idrogeologica, Consiglio Nazionale delle Ricerche, Italia

Petru Urdea, West University of Timișoara, Romania

Piotr Gebica, University of Rzeszów, Poland

Philip Deline, Université de Savoie, France

Sandu Boengiu, University of Craiova, Romania

Sipos Gyuri, University of Szeged, Hungary

Sunil Kumar De, North Eastern Hill University, India

Zofia Raczowska, Institute of Geography and Spatial Organization, Poland

Technical Board:

Journal manager: Florin Tătui, University of Bucharest, Romania

Layout editor: Sanda Roșca, Babeș-Bolyai University, Cluj-Napoca, Romania

Proofreading: Florin Zăinescu, Răzvan Popescu, University of Bucharest, Romania

Copyeditor: Mirela Vasile, Research Institute of the University of Bucharest, Romania

Cover Photo:

DTP: Meri Pogonariu

Address: Șos. Panduri, 90-92, București – 050663, România,

Phone/Fax: (0040) 021.410.23.84, E-mail: editura.unibuc@gmail.com,

Online bookshop: <http://librarie-unibuc.ro>,

Sale point: Bd. Regina Elisabeta, nr. 4-12, București

Tel. (0040) 021.314.35.08/2125

Web: www.edit.unibuc.ro

ISSN 1453-5068 ISSN online 2285-6773

CONTENTS

ARTICLES

An Analysis of Gorillas as Zoogeomorphic Agents

Andrea PIÑON, David R. BUTLER..... 5

Dendrogeomorphic reconstruction of past landslide activity in the Jablůnka village (Czech part of the Outer Western Carpathians)

Hana PŘECECHTĚLOVÁ, Karel ŠILHÁN 16

Seasonal and spatial variability of the morphodynamics of slopes within snow avalanche starting zones in the Tatra Mountains

Zofia RĄCZKOWSKA, Elżbieta ROJAN 27

Bioturbation by grizzly bears in relict solifluction features of Glacier National Park, Montana, USA: A case study Rock glaciers in mixed lithology: a case study from Northern Pirin

Carol F. SAWYER, Clayton J. WHITESIDES, Melanie B. STINE 40

MISCELLANEA

37th Romanian National Symposium on Geomorphology, Sinaia, Romania

Răzvan POPESCU 50

International Conference on Geomorphology, 10th Edition, Coimbra, Portugal

Laurențiu ȚUȚUIANU..... 52

An Analysis of Gorillas as Zoogeomorphic Agents

Andrea PIÑON¹, David R. BUTLER^{1*}

¹Department of Geography and Environmental Studies, Texas State University, San Marcos, TX 78666, U.S.A.

Received 9 April 2021; Revised 19 December 2022; Accepted 19 December 2022

*Correspondence to: David R. BUTLER; e-mail: db25@txstate.edu

ABSTRACT

Gorillas are among the most charismatic and well-researched species on the planet, yet their role as zoogeomorphic agents has gone largely overlooked. Knowledge on how gorillas contribute to landscape formation and decay is vital for future conservation planning and habitat suitability modelling. The purpose of this study is to conduct a content analysis of literature to identify gorilla zoogeomorphic activity and to aggregate and organize data into nine zoogeomorphic categories. Data obtained was used to provide a qualitative and quantitative summary of inter/intra-specific gorilla zoogeomorphic activity, and the extent of literature available on the subject. Categories of gorilla zoogeomorphic activity include: (1) soil scratching and (2) soil scraping of the forest floor; (3) excavating chambers and holes; (4) bare/semi-bare soil nest site building; (5) hand/knuckle and footprints; (6) excavating insect mounds; (7) tool use and associated geomorphic implications (8) trunk uprooting, and (9) trampling. All four gorilla sub-species (*G. gorilla*, *G. beringei*, *G. graueri*, *G. diehli*) were represented in the literature with evidence presented from nine countries in central Africa. Nest construction, mound disturbance, and excavated surface depressions were most frequently documented. Nests and mounds each made up 22 percent and excavated holes encompassed 16 percent of the literature. Soil-scraping, tool use, and trunk uprooting were poorly represented, making up 6 percent, 1 percent, and 2 percent of the total literature, respectively.

KEYWORDS Gorilla, Zoogeomorphology, Geomorphology, Primate, Africa

1. Introduction

Gorillas (*Gorilla spp.*) are among the most charismatic and well-researched species on the planet, yet their role as zoogeomorphic agents has been largely overlooked. Zoogeomorphology (Butler, 1992) is the study of animals as geomorphic agents, that is, their

role in sculpting, modifying, and maintaining the Earth's physical surface. Animals transport, erode, and displace earth material through their burrowing, wallowing, trampling (Butler, 1992) and building of dens, nests, and dams (Butler and Sawyer, 2012).

Gorillas exert an exceptional degree of geomorphic influence. They biomechanically transform the earth's surface by removing and transporting earth material to exploit food resources within their habitats. Their behaviour elicits a biotic–abiotic two-way interaction that results in a physical landscape imprint. This signature then becomes susceptible to

other exogenic forces that initiate and exacerbate local geomorphic processes, thereby, maintaining topographic transformation (Fig. 1a). In some cases, weathered and eroded areas will improve access to resources which encourages future biomechanical activity (Fig. 1b). Figure 1 illustrates a conceptual model of these processes.

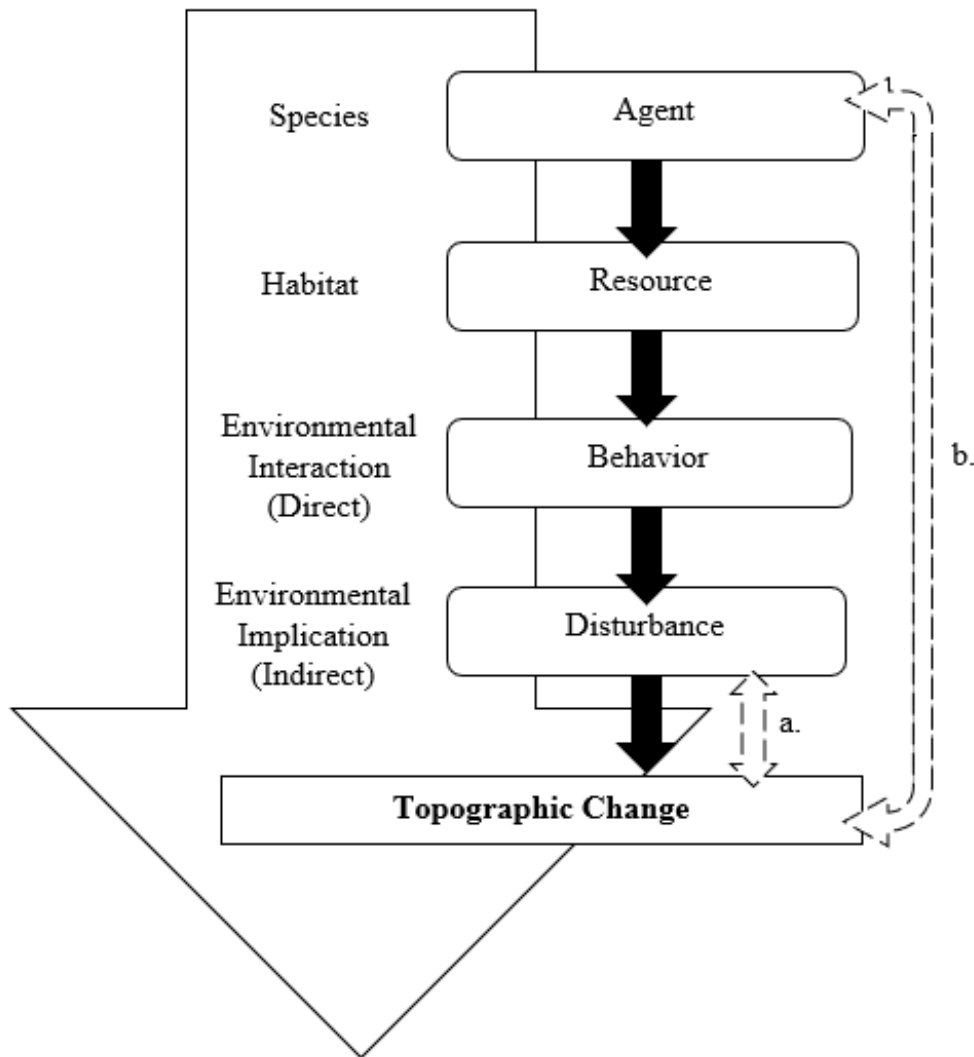


Figure 1 Conceptual model of gorilla zoogeomorphology and associated feedback mechanisms

Currently, reports of gorilla zoogeomorphic activity are scattered throughout the literature of various disciplines and mostly functions as supplementary data to primary research goals. Emphasis lies on phylogenetics, socio-behavioural and feeding ecology, with limited zoogeomorphic data. Nest site research has been the most successful in illustrating the extent of earth material excavated by gorilla. Their relatively large size and ubiquitous nature

makes nest constructions easier to detect in dense forest landscapes.

Early studies by Schaller (1963) and Fossey (1983) contributed some of the first accounts of gorilla zoogeomorphology. Schaller (1963) published detailed illustrations of nest site topographic spatial arrangement and quantified data of surface disturbance stemming from gorilla geophagy.

Table 1 Examples of gorilla zoogeomorphic activity. Impacts cited from Butler (1995)

Category	Species	Site	Activity	Impact	Source
Soil Scratching	<i>G. gorilla</i>	N-NNP	465 soil-scratching traces in search of insects	Pedoturbation, increased soil infiltration, vegetation removal, surface and slope instability and collapse, rock and soil transport, erosion	Nishihara and Kuroda, 1991
Soil Scraping	<i>G. beringei</i>	VNP	5m x 2m bare soil patch on slopes created from individuals observed engaging in geophagy	Pedoturbation, increased soil infiltration, vegetation removal, surface and slope instability and collapse, rock and soil transport, erosion	Schaller, 1963
Excavated Chambers & Depressions	<i>G. beringei</i>	VNP	Holes ranging between 13 cm–30 cm (depth) x 13 cm–25 cm (width) excavated by gorillas digging for plant roots	Surface and slope instability, erosion, transport and deposition of earth material, pedoturbation, pit and mound microtopography	Schaller, 1963
Bare & Semi-bare soil bottom nest site	<i>G. beringei</i>	VNP	1 gorilla observed digging day nest into hillside to create a sitting platform	Pit and mound microtopography, plant seed nursery sites, erosion, surface and slope instability, increased soil fertility, transport and deposition of earth material	Schaller, 1963
Excavated Insect Mounds	<i>G. gorilla</i>	LR	Gorillas broke apart 54 <i>Cubitermes sp.</i> mounds	Transport and deposition of earth material, erosion, increased soil infiltration and fertility, pedoturbation of termitaria and soil surface	Tutin and Fernandez, 1983
Trampling	<i>G. beringei</i>	VNP	Evidence of 15m ² trampled area in bamboo habitat within Mt. Visoke–Mt. Karisimba saddle region	Erosion, reduction and/or complete loss of vegetation, increased soil bulk density, soil fertility from animal feces, formation of slope treads	Plumptre, 1993
Hand/knuckle & footprints	<i>G. beringei</i>	N-NNP	466 traces of gorilla hand and/or footprints	Transport and deposition of earth material, pedoturbation, erosion	Nishihara and Kuroda, 1991
Trunk Uprooting	<i>G. beringei</i>	VNP	Gorilla uprooted tree at base to break ant mound	Pit and mound microtopography, vegetation loss, erosion	Watts, 1989
Tool Use	<i>G. gorilla</i>	N-NNP	1 observation of female using detached trunk as postural support to test water depth as she crossed swamp	Pit and mound microtopography, vegetation loss, erosion	Breuer, Ndoundou–Hockemba, and Fishlock, 2005

Two decades later, Dian Fossey (1983) reported a brief account of a cavern created by seasonal gorilla "soil-eating binges on Visoke's ridges" (52), a phenomenon hypothesized because of the soil's high calcium and potassium content (Fossey, 1983; Mahaney, 1993). She observed the subsequent effect of the surrounding root architecture in adapting and eventually supporting the 'eaten' chasm, a form of phytogeomorphic activity. Within the same region, Plumptre (1993) noted extensive trampling in the saddle region located between Mt. Visoke and Mt. Karisimba in Volcanoes National Park (VNP). It was caused by the extensive use by *G. beringei* as access trails between resting sites and food sites. Nishihara and Kuroda (1991) conducted the first and only detailed field study of *G. gorilla* soil-scratching behaviour. They determined this behaviour to be a

seasonal phenomenon exhibited during the wet season when the soil became softer and easier to break. Table 1 provides more examples of gorilla zoogeomorphic activity.

Gorillas are important biomodifiers that contribute to soil displacement, mass movement, and pedoturbation. Their landscape constructions (e.g., Fossey, 1983) create new habitat for sympatric species potentially making them ecosystem engineers. The purpose of this study was to explore gorilla behaviour and habitat use through the lens of zoogeomorphology. A content analysis of literature found either in print or online within twenty nine journals, four books, and seven organization webpages (Table 2) was exhaustively mined to capture the greatest extent of data possible.

Table 2 Content reviewed (1963–2014)

Journal	
African Journal of Ecology	Journal of Biogeography
African Journal of Physical Anthropology	Journal of Human Evolution
American Journal of Primatology	Journal of Mammalogy
Animal Behaviour	Journal of Primatology
Behavioural Processes	Journal of Tropical Ecology
Biodiversity and Conservation	Journal of Zoology
Biotechnology, Agronomy, Society and Environment	Nature
Ecological Applications	PloS Biology
Folia Primatol	PloS One
Folia Primatologica	Primate Conservation
Forest Ecology and Management	Primates
International Journal of Primatology	Stochastic Environmental Research & Risk Assessment
Journal of Applied Ecology	Tropics
Book	Organization
Gorilla Biology: A Multidisciplinary Perspective	Dian Fossey Gorilla Fund International
Gorillas in the Mist	The Cross River Gorilla Conservation Program
The Mountain Gorilla. Ecology and Behavior	The Leakey Foundation
Mountain Gorillas. Three Decades of Research at Karisoke	World Wildlife Fund
	United States Fish and Wildlife Service
	World Resources Institute
	International Union for Conservation of Nature and Natural Resources

Table 3 Identified gorilla zoogeomorphic categories and their descriptions

Category	Description
1. Soil scratching	Scratching of the forest floor with hands.
2. Soil scraping	Scratching of the forest floor with incisors.
3. Excavated chambers and depressions	Excavation of soil horizon greater than 13 cm (5 in).
4. Bare/semi-bare soil nest sites	Individual or group nests constructed entirely of soil or with soil exposed nest cup bottom and herbaceous rim.
5. Insect mound excavations	Mechanical dismantling of insect mounds.
6. Trampling	Soil compaction along frequently used individual and group feeding/ranging trails with clear reduction or complete loss of vegetation.
7. Hand/Knuckle and footprints	Soil surface indentations of prints.
8. Tool use	Earth surface disturbance resulting from the use of detached object as a tool.
9. Trunk uprooting	Uprooting of shrub and tree trunks.

Under the auspices of published zoogeomorphology studies on other animals, this study organized data collected from the literature into nine categories of gorilla zoogeomorphic activity (Table 3). These include (1) soil scratching (with hands) and (2) scraping (with incisors) of the forest floor; (3) chambers and depressions created from surface excavation; (4) bare and semi-bare soil nest site constructions; (5) insect mound excavation; (6) trampling; (7) hand/knuckle and foot prints; (8) surface disturbance as a result of tool use; and, finally, (9) trunk uprooting (e.g., Schaller, 1963; Casimir, 1979; Fossey, 1983; Carroll, 1986; Mahaney, Watts and Hancock, 1990; Nishihara and Kuroda, 1991; Plumptre, 1993; Remis, 1993; Tutin and Parnell, 1995; Breuer, Ndoundou-Hockemba and Fishlock, 2005; Wittiger and Sunderland-Groves, 2007).

The knowledge that could be generated on the zoogeomorphic impacts of gorillas is far-reaching. Do *Gorilla spp.* contribute to landscape formation and decay? If they do, to what extent do they impact and initiate geomorphic processes? This study begins answering these questions and represents the first of its kind dedicated to examining existing data through the lens of zoogeomorphology.

2. Data

Raw data was generated using printed and online literature published between 1963 and 2014 in twenty nine journals, four books, and seven government and non-profit organization websites (Table 2). Key words such as, "gorilla and nest" or "gorilla and scratch" initiated the search, and afterwards, author-supplied key terms and database subject terms guided future searches. Journals listed in Table 2 were not initially selected for the literature review, rather, the list was generated from relevant articles collected for the content analysis. The purpose of initiating searches using key terms instead of journals was to mitigate the issue of fragmented data published in journals from multiple disciplines. The definition of zoogeomorphology served as a guide to identify and aggregate the data into nine categories (Table 3) of gorilla zoogeomorphic activity.

3. Methods

3.1 Region and species

The tropical climate in central Africa has distinct long wet seasons (September through June) with heavy precipitation exceeding 2,000 mm (80 in). The

dry season (July through August) is brief with precipitation decreasing towards the east and west coasts and with increasing latitude from the Equator. Average annual temperatures range from 25–28°C (77°F to 82°F) (Kayiranga et al., 2017). Vegetation is characterized by a patchwork of primary and secondary evergreen and deciduous mixed-species, tropical lowland and montane rainforest with marshy clearings and gallery forests (Mehlman and Doran, 2002). This region is recognized for its high level of biodiversity, endemism, and location of one of the largest tracts of intact contiguous tropical forest. The Congo and Nile River are the two primary watersheds in the region. The Congo Basin drains an area of $\sim 3.8 \times 10^6 \text{ km}^2$ and contributes 50 per-

cent of all annual freshwater discharge ($\sim 1300 \text{ km}^3$) from central Africa to the Atlantic (Upstill-Goddard et al., 2017). The Nile River has a drainage area of $3,176,541 \text{ km}^2$ that stretches across 11 countries (6,695 km) (Belete et al., 2018).

This study examined peer reviewed articles on wild gorilla populations (Fig. 2) with no limitations on the length of the study period. There were no set requirements for the year of publication. Simply, the literature was mined as early as zoogeomorphic data was made available. All four sub-species of gorilla taxa were included with no preference given to the number of individuals or size of group observed. Subjects also included extinct and extant populations in protected regions of central Africa.

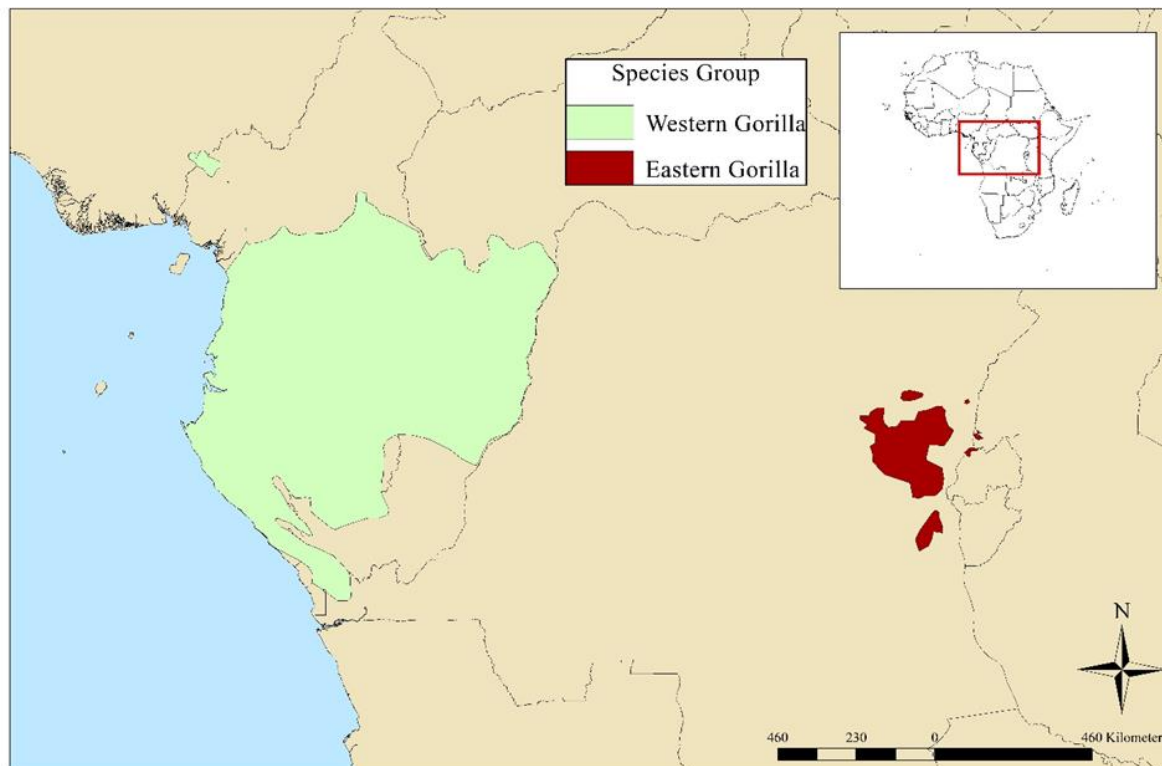


Figure 2 Gorilla population distribution in central Africa

3.2 Analysis

This content analysis was conducted using fundamental principles of zoogeomorphology and wildlife ecology to uncover new insights on existing literature and guide the systematic classification of categories and sub-categories. Subject areas in gorilla habitat use, movement and foraging patterns, and food and resource selection were mined for zoogeomorphic activity. Information was organized

by sub-species, protected region, and qualitative and quantitative data. Aggregate data sets and descriptive information was derived using measures of central tendency (mean, median, mode) and dispersion (standard deviation). If data provided in the literature was a range, the median was taken from that range (e.g., 13–30 cm depth of excavated hole, median = 21.5) and that value used in the meta-analysis.

4. Results

A total of 106 documented cases of zoogeomorphic activity were recovered from the content analysis. A total of nine protected regions in Central Africa were represented in the content analysis. These include (1) Dzanga–Sangha Dense Forest Reserve (–SDFR) and (2) Dzanga–Ndoki National Park (D–NNP), Central African Republic; (3) Nouabalé–Ndoki National Park, Republic of the Congo; (4) Volcanoes National Park (VNP), (5) Virunga National Park (ViNP), (6) and Kahuzi–Biega National Park, (K–BNP), Democratic Republic of the Congo; (7) Lope Reserve (LR) and (8) Moukalaba–Doudou National Park (M–DNP), Gabon; and Dja Biosphere Reserve (DBR), Cameroon.

Soil scraping, tool use, and trampling zoogeomorphic activity was least documented in the literature indicating a critical need for research. The earliest documentation of zoogeomorphic activity was by Schaller in 1963 on his study of *G. beringei* in VNP. The latest was a 2014 study on *G. gorilla* nest sites in the DBR.

4.1 Soil scratching

Soil scratching is the mechanical manipulation of the physical surface using fingers and toes. Raking of soil removes or degrades surface vegetation resulting in decreased surface stability, increased soil infiltration and pedoturbation of surface material. Depressions of highly scratched areas can incise and widen from exogenic fluvial processes that erode and transport material.

Evidence of scratching was documented among 3 sub-species of gorilla (*G. gorilla*, *G. beringei*, *G. graueri*) within 5 protected regions (D–NNP, D–SDFR, K–BNP, N–NNP, VNP). The content analysis demonstrated that 10 percent (n=11) of the literature, across all zoogeomorphology categories (n=106), documented gorilla soil scratching.

Observed scratching bouts were most frequent with only a single publication (Nishihara and Kuroda, 1991) dedicated to this subject. Their article was the sole provider of photographs of soil scratching traces. Moreover, their study documented 465 traces of soil that had been scratched at an average frequency of 0.84 traces/km².

4.2 Soil scraping

Soil scraping is the mechanical manipulation of the physical surface using the incisors. Gorillas exhibit sexual dimorphism in their dental morphology. The mean length of a canine pair ranges from 10.8 mm (adult female, Booth, 1971) up to 33.58 mm (adult male, Manning and Chamberlain, 1994) making them efficient soil masticating machines. Soil scraping was documented among *G. beringei* only. This form of zoogeomorphic activity results in decreased bulk density, increased soil infiltration, and loss of surface stability from earth material removal (e.g., rocks, ground vegetation). Evidence for scraping consisted of identification of disturbed sites, bout observation, and indirect evidence (e.g., soil smeared gorilla faces, Schaller, 1963). The content analysis returned documented evidence of 4 sites where gorillas had scraped the floor. Tooth marks were located on small, vertical bluffs situated on exposed layers of quartz and white stone (Schaller, 1963). Schaller (1963) noted a scraped soil patch located on a slope on Mt. Mikeno, VNP, that measured 5 m long x 2 m wide. Literature was scarce on this subject with scraping data making up 6 percent (n=6) of all zoogeomorphic data retrieved from the content analysis (n=106) across all categories.

4.3 Excavated chambers and depressions

Digging by gorillas leaves significant physical impressions on the landscape that vary in size and shape. Biomechanical transformation of the landscape leads to pedoturbation and erosion; and if located on slopes, the movement of material downslope and backfilling of holes (Butler, 1995). Excavations for this category range as small as 17 cm³ (derived from meta-analysis) of displaced soil from plant uprooting to large caverns created from incessant geophagy by gorilla groups (e.g., Fossey, 1983, 53). Publications documenting this type of zoogeomorphic activity mostly encompassed gorilla digging bouts. A meta-analysis of this data returned a total of 8 observations of gorillas digging holes, mostly for sub-surface plant parts to consume. In one of those instances, an author noted holes created from the ripping and dismantling of grass and mud by a gorilla during a display behaviour (Wittiger and Sunderland Groves, 2007). Only two

articles (Schaller, 1963; Yamagiwa et al., 1991) measured hole dimensions. 16 percent (n=17) of zoogeomorphic peripheral data recovered from the content analysis (n=106), across all categories, provided documentation of pits and depressions. Three subspecies (*G. diehli*, *G. beringei*, *G. graueri*) within 5 protected areas (K-BNP, KGS, ViNP, VNP) were found to be zoogeomorphically active. The most significant report of landscape formation was the creation of a large cavern (no dimensions provided) located in VNP that had been so highly incised from gorilla geophagy that it became large enough to allow individuals to enter and feed on the soil (Fossey, 1983).

4.4 Bare/semi-bare soil bottom nest site

Gorillas construct day and night nests with limited topographic restrictions on location. Nest construction results in morphological changes to the surface that include pit-mound topography, surface instability, pedoturbation, and erosion. Constructions have been found on ridges, saddle regions, and variable slope (flat–40°) terrain. Because of their conspicuous nature, they are one of the most researched zoogeomorphology categories (22% of literature included in content analysis, n=106). For this study, only nest sites with fully exposed and partial-bare soil nest cups were considered. Zoogeomorphic activity found in the literature includes direct and indirect evidence of nest site construction.

A meta-analysis of the data revealed a total of 2851 individual soil nest sites with an average life span of 4.3 days for bare soil sites and 19.1 days for semi-bare soil nests (Blom et al., 2001). A total of 379 group nesting areas were counted where either all individuals in the group constructed a soil nest or at least one soil nest was accounted for in the literature. Only one observation of a gorilla engaging in day nest construction was found in the literature. Unfortunately, only a single depth measurement of a nest cup (38 cm) was recovered from the literature from Schaller (1963). He also noted a nest rim made from nearby vegetation constructed 61 cm high from the surface. The gorilla rested on the soil bottom.

4.5 Excavated insect mounds

Gorillas search for surface and subsurface dwelling insects (e.g., ants, termites) to consume by mechanically dismantling or digging up mounds. Fragments are then further broken apart to reveal insects (Cipolletta et al., 2006). It is a patchily distributed and seasonal behaviour that results in faunal turbation of termitaria and surface soil, and in situ weathering and erosion of mound pits. Four articles documented zoogeomorphic impacts from mound excavation for *G. gorilla* and *G. beringei* within four protected areas (i.e., D-SDFR, D-NNP, LP, VNP). Data consisted of observed bouts of mound dismantling, number of visits to mounds, and evidence of disturbance where there was no gorilla present but adjacent knuckle prints were clearly visible next to mound. A meta-analysis of data in the literature revealed that soil particles ranged in size from 3 cm to 50 cm wide ($\bar{x}$ =13.5 cm, n=203). Cipolletta et al. (2006) recorded soil bits that reached 5cm in length. 540 bouts of gorillas excavating mounds were documented with a total of 150 observed minutes. On average gorillas spent 25 minutes breaking apart mounds. A total of 764 affected mounds were accounted for in the literature. 506 were insect nests constructed against large trees. 9 nests had to be dug out of the ground, and 94 were free-standing mounds. 96 broken mounds were broken to harvest *Cubitermes sp* and 5 to access *Dorylus sp*. A total of 446 ($\bar{x}$ =111) visits to mounds were counted. No data could be found on the extent of displaced soil or size of pits created.

4.6 Trampling

Trampling occurs when frequently used areas result in a visible contrast between degraded areas of vegetation loss and adjacent areas with intact surfaces. Trampling alters plant communities by compacting the soil and influencing infiltration rates and leads to physio-chemical changes from compaction and deposition of faecal matter (Butler, 1995). Trampling has been documented among eastern gorillas (*G. beringei*, *G. graueri*) within VNP only. *G. beringei* had the greatest impact in bamboo habitats with a total of 10 m² of affected area and in the saddle region of VNP, evidence of 5 m² (Plumptre, 1993) of trampling. A meta-analysis of *G. graueri*

ranging data gathered from Yamagiwa (1991) returned a total average distance travelled (m) between feeding sites of 695 m. From that total, 237 m were travelled between two ant feeding sites and the remaining 458 m were between ant feeding sites and "other" (250) feeding sites. Gorillas targeted 8 sites located on ridges and 10 sites on slopes (no percent gradient provided). Although no evidence of trampling was provided, the author cited frequent insectivore during the wet and dry seasons. This leads to the assumption that some degree of trampling exists on the condition that the same feeding sites are consistently targeted. To gain an understanding of potential pressure exerted on the surface from ranging, a meta-analysis of average touch-off pressure (N/cm²) data (Matarazzo, 2013) was conducted. Seven captive individuals (3 silverbacks, 4 adult females) exert a total average pressure of 14.07 N/cm²/hand (20.41 lbs/in²; 28.14 N/cm², 40.81 lbs/in² for both hands) and an average 2.01 N/cm²/hand (2.91 lbs/in²; 4.02 N/cm², 5.83 lbs/in² for both hands) of pressure per individual. Gorilla groups range from 2–30 individuals per group (Schaller, 1963), therefore, the degree of pressure exerted on the earth's surface ranges between 8.04 N/cm² (11.6 lbs/in²) of pressure for small groups and a maximum 120.6 N/cm² (174.9 lbs/in²) of pressure for large groups. These values will vary with group structure, area, and habitat use. The primary argument is that gorillas have the potential for extensive trampling and transformation of surface dynamics. Further research is needed to document their zoogeomorphic imprint.

4.7 Hand/knuckle and footprints

Gorillas exhibit primarily quadrupedal knuckle-walking locomotion with occasional bipedalism (Matarazzo, 2013). Their weight (136–68 kg) and the extent of surface area covered by their foot and knuckle prints initiates variable degrees of geomorphic influence on access trails. Transport and mixing of soil occur when dirt is sucked beneath their feet and hands and is deposited in other locations. These effects are pronounced in soft terrain such as mud and sand where imprints can be deep. A meta-analysis of Schaller's (1963) measurements of gorilla tracks returned an average disturbed surface area of 134.4 cm² (12.8 cm width by 10.5 cm

length) for one knuckle print and 409.2 cm² (15.1 cm width by 27.1 cm length) for one footprint. Theoretically, if all four extremities are considered, one individual has the potential to impact 0.026 m² of surface area with both knuckles and 0.081 m² with both feet in a single step. Gorillas exhibit an even distribution of surface pressure along their knuckles when they touch-off the ground during movement. A total of 466 tracks and 54 trails with clear foot and knuckle prints were accounted for in the literature. Cipolleta et al. (2006) noted *G. gorilla* knuckle prints during 13 days in the field. The content analysis indicated studies documenting surface disturbance from foot and knuckle prints was scarce compared to other zoogeomorphology categories. Six individual accounts of measured earth disturbance (all from Schaller, 1963) made up 13 percent of quantified zoogeomorphic data sets (n=45) available across all categories. Three cases of either observed zoogeomorphic behaviour or physical indications of zoogeomorphic activity made up 5 percent of all qualitative zoogeomorphic data sets (n=61) available across all categories. Together, available data suggesting the geomorphic significance of gorilla tracks is a mere 8 percent (n=106) indicating a need for more research.

4.8 Tool use

The definition of tool use has undergone multiple revisions and is a behaviour rarely observed among wild gorillas (Grueter et al., 2013). Beck's (1980) definition is widely accepted and defines tool use as "*the external employment of an unattached environmental object to alter more efficiently the form, position, or condition of another object, another organism, or the user itself when the user holds or carries the tool during or just prior to use and is responsible for the proper and effective orientation of the tool*". The content analysis revealed one observed occurrence of tool use of geomorphic significance. Breuer, Ndoundou-Hockemba, and Fishlock (2005) documented a female *G. gorilla* that used a detached tree branch to probe swampy substrate to test the water depth in front of her as she attempted to cross. Within the context of zoogeomorphology, emphasis is not on the behaviour but on the geomorphic implications. The prodding action and wading by the gorilla contribute to mixing and

transport of swamp bottom substrate and disrupts the structural function of hydrophytic vegetation if disturbed.

4.9 Trunk uprooting

Trunk uprooting is the mechanical displacement of shrubs or trees resulting in pit-mound microtopography which contributes to local soil erosion and mixing of horizons. The destabilizing effects of trunk uprooting are pronounced on slopes (Pawlik, 2013) when the structural root architecture is removed. Two articles documenting this activity were obtained from the content analysis making up 1.8 percent of all zoogeomorphic datasets (n=106) available across all categories. No attempts were taken to measure the degree of soil displaced from the resulting pit-mound formations. Watts (1989) observed a male silverback uproot a tree trunk to dismantle an ant mound supported by its base. Breuer, Ndoundou-Hockemba, and Fishlock (2005) witnessed a female uproot a small tree trunk (approximately 1.3 cm long and 5 cm thick) at the edge of a swampy clearing. She used the trunk with one hand to stabilize herself while she dredged aquatic herbs towards her with the other arm.

5. Conclusion

Gorillas have captured the attention of researchers from many scientific disciplines, but few studies have provided detailed zoogeomorphological data on their impacts on the landscape. Current studies on these increasingly threatened animals have made substantial contributions to their protection and conservation of their habitats. Lacking is research exploring the role of gorillas as zoogeomorphic agents.

This study has identified nine categories of zoogeomorphic impacts by gorillas, all of which require additional quantification. Those categories include: (1) soil scratching and (2) soil scraping of the forest floor; (3) excavating chambers and holes; (4) bare/semi-bare soil nest site building; (5) hand/knuckle and footprints; (6) excavating insect mounds; (7) tool use and associated geomorphic implications (8) trunk uprooting, and (9) trampling.

Gorilla zoogeomorphic activity presented are intended to lay the grounds for future field study and

invite new research insights into one of the most well-explored species on the planet. Research is necessary to refine our understanding of their role as bio-modifiers. Without this knowledge, vital pieces of information could be excluded in future conservation planning and habitat suitability modelling.

References

- Beck B. 1980. *Animal Tool Use*. Garland STPM Press New York NY.
- Belete M, Deng J, Zhou M, Wang K, You S, Hong Y, Weston M. 2018. A new approach to modeling water balance in Nile River Basin, Africa. *Sustainability* **10**(3): 810–824.
- Blom A, Kpanou JB, Prins HHT, Almaši A, Heitkönig IMA. 2001. A survey of the apes in the Dzanga–Ndoki National Park, Central African Republic: A comparison between the census and survey methods of estimating the gorilla (*Gorilla gorilla gorilla*) and chimpanzee (*Pan troglodytes*) nest group density. *African Journal of Ecology* **39**(1): 98–105.
- Booth S.N. 1971. Observations on the teeth of the mountain gorilla (*Gorilla gorilla beringei*). *American Journal of Physical Anthropology* **34**(1): 85–88.
- Breuer T, Ndoundou-Hockemba M, Fishlock V. 2005. First observation of tool use in wild gorillas. *PLoS Biology* **3**(11): e380.
- Butler DR. 1992. The grizzly bear as an erosional agent in mountainous terrain. *Zeitschrift für Geomorphologie* **36**(2): 179–189.
- . 1995. *Zoogeomorphology – Animals as geomorphic agents*. Cambridge University Press New York NY.
- Butler DR, Sawyer CF. 2012. Introduction to the special issue – zoogeomorphology and ecosystem engineering. *Geomorphology* **157–158**(2012): 1–5.
- Carroll RW. 1986. Status of the lowland gorilla and other wildlife in the Dzanga–Sangha Region of southwestern Central African Republic. *Primate Conservation* **7**: 38–41.
- Casimir MJ. 1979. An analysis of gorilla nesting sites of the Mt. Kahuzi region (Zaire). *Folia Primatologica* **32**(4): 290–308.
- Cipolletta C, Spagnoletti N, Todd A, Robbins MM, Cohen H, Pacyna S. 2006. Termite feeding by Gorilla gorilla gorilla at Bai Hokou, Central African Republic. *International Journal of Primatology* **28**(2): 457–476.
- Fossey D. 1983. *Gorillas in the Mist*. Houghton Mifflin Company Boston MA.

- Grueter CC, Robbins MM, Ndagijimana F, Stoinski TS. 2013. Possible tool use in a mountain gorilla. *Behavioural Processes* **100**: 160–162.
- Kayiranga A, Ndayisaba F, Nahayo L, Karamage F, Nsengiyumva JB, Mupenzi C, Nyesheja EM. 2017. Analysis of climate and topography impacts on the spatial distribution of vegetation in the Virunga Volcanoes massif of east-central Africa. *Geosciences (Switzerland)* **7**(17): 1–18.
- Mahaney WC. 1993. Scanning electron microscopy of earth mined and eaten by mountain gorillas in the Virunga Mountains, Rwanda. *Primates* **34**(3): 311–319.
- Mahaney WC, Watts DP, Hancock RGV. 1990. Geophagia by mountain gorillas (*Gorilla gorilla beringei*) in the Virunga Mountains, Rwanda. *Primates* **31**: 113–120.
- Manning JT, Chamberlain AT. 1994. Fluctuating asymmetry in gorilla canines: A sensitive indicator of environmental stress. *Proceedings: Biological Sciences* **255**(1343): 189–193.
- Matarazzo S. 2013. Manual pressure distribution patterns of knuckle-walking apes. *American Journal of Physical Anthropology* **152**(1): 44–50.
- Mehlman PT, Doran DM. 2002. Influencing western gorilla nest construction at Mondika Research Center. *International Journal of Primatology* **23**(6): 1257–1285.
- Nishihara T, Kuroda S. 1991. Soil-scratching behaviour by western lowland gorillas. *Folia Primatol* **57**(1): 48–51.
- Plumptre AJ. 1993. The effects of trampling damage by herbivores on the vegetation of the Parc National des Volcans, Rwanda. *African Journal of Ecology* **32**(2): 115–129.
- Remis MJ. 1993. Nesting behavior of lowland gorillas in the Dzanga–Sangha Reserve, Central African Republic: Implications for population estimates and understandings of group dynamics. *Tropics* **2**(4): 245–255.
- Schaller G B. 1963. *The Mountain Gorilla. Ecology and Behavior*. The University of Chicago Press Chicago IL.
- Tutin CEG, Fernandez M. 1983. Gorillas feeding on termites in Gabon, West Africa. *Journal of Mammalogy* **64**(3): 530–531.
- Tutin CEG, Parnell RJ. 1995. Nest building by lowland gorillas in the Lope Reserve, Gabon: Environmental influences and implications for censusing. *International Journal of Primatology* **16**(1): 53–76.
- Upstill-Goddard R, Salter ME, Mann PJ, Barnes J, Poulsen J, Dinga B, Fiske GJ, Holmes RM. 2017. The riverine source of CH₄ and N₂O from the Republic of Congo, western Congo Basin. *Biogeosciences* **14**(9): 2267–2281.
- Watts DP. 1989. Ant eating behavior of mountain gorillas. *Primates* **30**(1): 121–125.
- Wittiger L, Sunderland–Groves J. 2007. Tool use during display behavior in wild cross river gorillas. *American Journal of Primatology* **69**(11): 1307–1311.
- Yamagiwa J, Mwanza N, Yumoto T, Maruhashi T. 1991. Ant eating by eastern lowland gorillas. *Primates* **32**: 247–253.

Dendrogeomorphic reconstruction of past landslide activity in the Jablůnka village (Czech part of the Outer Western Carpathians)

Hana PŘECEHTĚLOVÁ¹, Karel ŠILHÁN^{1*}

¹Department of Physical Geography and Geoecology, Faculty of Science, University of Ostrava, Czech Republic

Received 28 January 2022; Revised 31 November 2022; Accepted 19 December 2022

*Correspondence to: Karel ŠILHÁN; e-mail: karel.silhan@osu.cz

ABSTRACT

Landslides represent an important and possibly very dangerous natural hazard. Dendrogeomorphic methods can provide unique data on the behaviour of landslides in the past by studying the tree-ring series of disturbed trees. Knowledge about past landslide activity in the flysch part of the Outer Western Carpathians is generally very scarce or missing. The past activity of selected landslides (possibly endangering neighbouring settlements) was studied using data from 106 increment cores from 53 disturbed individuals of *Picea abies* (L.) H. Karst. to assess their past spatiotemporal activity. In total, six certain event years and 13 probable events were detected during the period between 1927 and 2017. Certain events always occurred in groups of the two following events, suggesting the inertia of landslide movements after the initial triggering. The spatiotemporal reconstruction revealed a distinctly increased activity of movements in the zone of the main scarp and particularly in the landslide front, which could possibly endanger human infrastructure during its significant reactivation. However, the reconstruction performed suggests general landslide inactivity since 1997, when the last high-magnitude reactivation occurred.

KEYWORDS Dendrogeomorphology; Landslide; Dendrometry; Outer Western Carpathians; Reaction wood

1. Introduction

Landslide movements can represent a high risk for the inhabitants living in their surroundings. Damage to buildings or roads is no exception (Kirchner et al., 2000). The activity of slope processes is currently one of the most important pieces of information for

understanding these natural hazards and their triggers (Corominas a Moya, 2008). Several possibilities of landslide movement monitoring exist, i.e., installation of extensometers (Klimeš et al., 2012), repeated GNSS measurements (Wang, 2011), or digital

photogrammetry (Chandler, 1999). The use of such methods can be limited by the necessity of long-term monitoring and approach precision due to the lack of obtained information.

One of the oldest known landslide events in the Hostýnsko–Vsetínská highland (Czech part of the Outer Western Carpathians – one of the most landslides-susceptible regions in central Europe (Van den Eeckhaut and Hervás, 2012)) probably originated in 1924–1929 (Bil et al., 2014). However, the landslide movements recorded a higher interest after the landslide calamity in 1997, when the extreme precipitation total amount (re)activated slope movements in the flysch relief of the Outer Western Carpathians in the eastern part of the Czech Republic and caused extensive damage (Kirchner and Krejčí, 2002). The region around Vsetín town was one of the most heavily damaged (Kirchner and Krejčí, 2002). The main triggering factors of landslide reactivation in this region are extreme (high-magnitude) precipitation totals and intensive snow melt (often in combination with rain on snow) (Kirchner and Krejčí, 2002).

To determine past landslide activity and creation of event chronology, dendrogeomorphic methods can be used as very effective tools in situations where archival data or long-term monitoring is missing (Alestalo 1971). The length of the reconstructed chronology of past landslide movements can reach several hundred years or up to a millennium (Zhang et al., 2019), even with seasonal precision (Lopez-Saez et al., 2012a). The first mention of the term dendrogeomorphology was by Alestalo (1971), who described the basic relationships between slope movements and tree growth by Shroder (1978), who introduced the process–event–response scheme that is currently valid. Later, dendrogeomorphic methods were frequently used for studying various geomorphic processes (Stoffel et al., 2008; Bollschweiler et al., 2009), hydrological processes (Ballesteros et al., 2011; Stoffel and Wilford, 2012), or geological applications (Jacoby et al., 1988; Baillie, 2008). Dendrogeomorphic methods use the analysis of tree-ring series of trees disturbed by geomorphic processes of interest (Stoffel and Bollschweiler, 2009). The information from disturbed tree ring series can help us

better understand the landslide behaviour in regions of interest (Šilhán, 2020). Moreover, data about past active landslides can be used not only for the assessment of landslide triggers but also for the modelling of landslide activities in the future (Lopez Saez et al., 2012b). Landslide movements usually cause tilting of the tree stems. The intensity and direction of stem tilting can be successfully used to assess landslide movement mechanisms (e.g., rotational vs. translational movements), as demonstrated by Šilhán (2015).

The aim of this study is to create a spatiotemporal reconstruction of past landslide movements in the forested area near Jablůnka village in the Hostýnsko–Vsetínská highland using dendrogeomorphic methods. The partial aim can be summarised as follows: i) to define the frequency and recurrence of landslide movements, ii) create the spatiotemporal reconstruction of past landslide activity in map form, and iii) verify the possible activity of the studied landslide in 1997. The obtained information can help with decisions about the extension of urbanised zones surrounding active landslides.

2. Studied locality

The studied landslide (49.38° N and 17.97° E; Fig. 1) is located at an elevation of approximately 500 m a.s.l. in the NW direction from the Vlčice Mt. (606 m a.s.l.) in the Hostýnsko–Vsetínská highland. The geological composition of the region is part of the flysch zone of the Outer Western Carpathians (the group of the Magura nappes). The area of interest is located in the Račanská unit of the Belovež layers. This structure is typical of fine flysch with dominating claystones over locally occurring sandstones of the Paleocene to Eocene age (Menčík et al., 1983). The average precipitation total amount reaches 100–130 mm during the summer half of the year and 130–160 mm during the winter half of the year (Tolasz et al., 2007). The maximal precipitation total was recorded in 1997 when the mean five-day (4–8 July) cumulated precipitation reached 300–400 mm. Several hundreds of landslides in the studied region were activated during this extraordinary event (Kirchner et al., 2000).

The landslide of interest has flow-like morphological characteristics with the expected shallow slip

surface. The landslide is approximately 300 m long and 100 m wide. The height of the morphological indistinct main scarp is approximately 1 m, and the landslide front is situated on the bank of the Lýkový stream. The landslide front is morphologically very distinct, with lobate fresh morphology suggesting its recent active movements. The evidence of active landslide movements starts in the middle zone of the total landslide area with a distinct tension crack on one side of the landslide. The erosion step is approximately located in the corresponding position to the crack on the opposite side of the landslide. The frontal part of the landslide is covered by juve-

nile individuals of common spruce (*Picea abies* (L.) H. Karst.). The rest of the landslide area is occupied by distinctly older individuals of *P. abies*. The forest cover in the upper part of the landslide is supplemented by juvenile individuals of European beech (*Fagus sylvatica* L.). The active landslide front is located approximately 400 m above the inhabited area, on the land of an industrial company. Possible fast acceleration of landslide movements could cause heavy damages here, as already happened in several localities in the studied region (Kirchner and Krejčí, 2002).

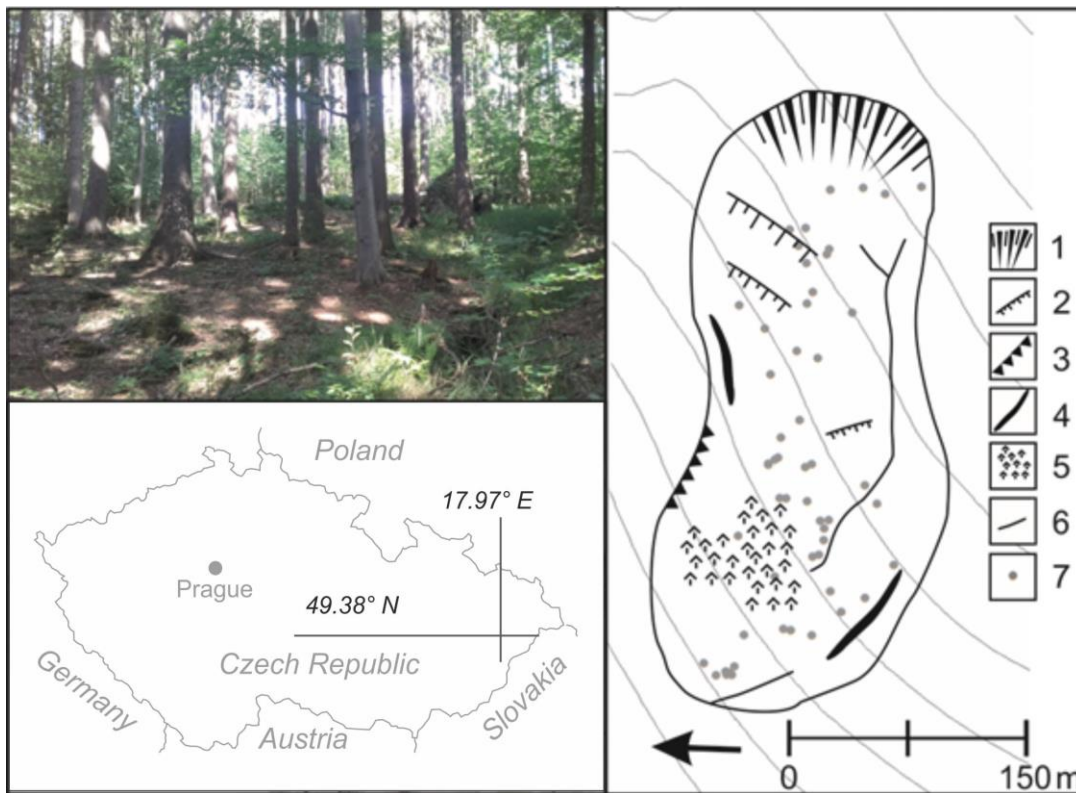


Figure 1 Location and geomorphology of the studied locality (1 – main scarp, 2 – terrain step, 3 – minor scarp, 4 – tension crack, 5 – juvenile trees, 6 – gully, 7 – sampled tree)

3. Methods

The main methodical approach used in this study was based on studying tree-ring series. Nonetheless, this method was supplemented by other approaches.

3.1 Geomorphic mapping

The first step of fieldwork included geomorphic mapping (1:100). The mapping was focused on the

basic structures of the landslide area (e.g., the presence and location of the main scarp, tension cracks, gullies, lateral levees; Fig. 1). The positions of all trees occupying the landslide area were simultaneously recorded using a total geodetic station. Next, the intensity and direction of stem tilting were measured and recorded using a digital inclinometer and compass. These dendrometric parameters were recorded for all trees occupying the landslide sur-

face (not only the sampled and analysed trees). Trees suitable for subsequent sampling and dendrogeomorphic analysis were selected during this step as well. The trees were selected according to their positions to equally cover the landslide surface, as recommended by Corona et al. (2014).

3.2 Field dendrogeomorphic sampling

All selected trees were sampled using a Pressler increment borer (maximum length: 50 cm; diameter: 0.5 cm). Only trees with evident effects on their growth by landslide movements (tilted or bent tree stems) were sampled (Kirchner and Lacina, 2004). In total, 53 individuals of *P. abies* were sampled, and their positions were recorded in the geomorphic map. Two increment cores were extracted from each tree.

The first core was taken from the lower side of the tilted stem and another from the opposite side of the stem. The sampling height was in the position of the most intensive stem bending. Next, 20 indistinguishable individuals of *P. abies* growing out of the studied landslide in the stable position but under similar microclimatic conditions were sampled for construction of the reference chronology. All reference trees were sampled in the isoline direc-

tion, and two increment cores were always taken from each tree.

3.3 Laboratory approaches

The processing of samples following standard dendrochronological procedures (Stokes and Smiley, 1968) preceded the interpretation of landslide signals in the tree-ring series of disturbed trees. Individual methodical steps included gluing the samples into wood supports and subsequent sanding of core surfaces by descending rows of sandpaper. The next analytical step was tree ring counting and measurement of their widths using the dendrochronological device TimeTable and PAST4 (VIAS, 2005) software under a binocular stereoscope.

Samples from reference trees were processed in the same way, and the resulting reference chronology was compiled in Arstan software (Holmes, 1994) using a double detrending procedure. Increment curves of reference chronology and individual disturbed trees were cross-dated to identify possible false or missing rings. Moreover, the reference curve was used to filter climatically induced growth and abrupt changes in tree growth from the geomorphic induced ones.

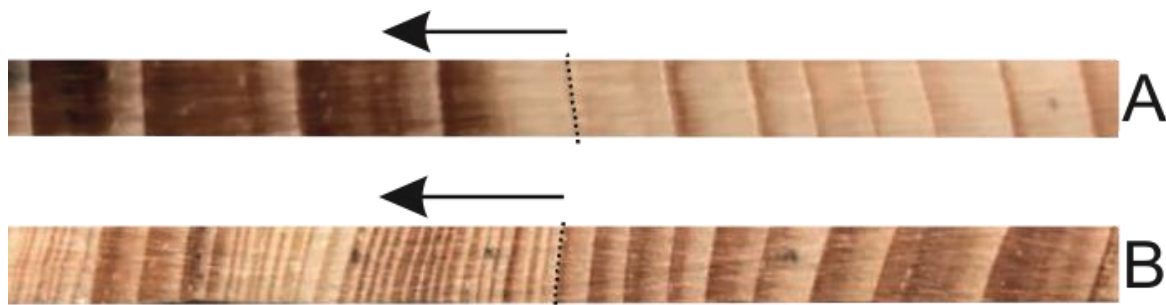


Figure 2 Dated growth disturbances. A – reaction wood, B – abrupt growth suppression

3.4 Sample analysis and identification of past landslide events

The prepared samples were macroscopically analysed for the detection of growth disturbances in individual years. The most frequent growth disturbance induced by tilting of the tree stem due to the destabilization of the tree ground via landslide movements was reaction wood (Fig. 2; Westing, 1965). The reaction wood in coniferous tree species is also called compression, whose typical characteristic is the occurrence of a wide tree ring with a dis-

tinctly darker colour on the lower side of the stem (Stoffel and Bollschweiler, 2009). The brown–reddish colour of woody material is caused by thick and well-rounded cell walls of early and late wood tracheids (Timell, 1986). The initial year of occurrence (the onset), the number of subsequent rings containing a compression wood structure and reaction wood type (mild or pronounced following the recommendation of Lopez Saez et al., 2012a) were the recorded parameters of each identified reaction wood. Mild reaction wood was defined when the

typical structure occurred in less than 75% of the tree-ring width, and the pronounced reaction wood was defined as the occurrence of reaction wood structure in more than 75% of tree-ring width (Lopez Saez et al., 2012a). The next observed and recorded growth disturbance was the abrupt changes in the tree ring widths (particularly decrease) in the several following tree rings (Fig. 2). Abrupt growth suppression is usually caused by damage to the root system by subsurface landslide movements or by the decapitation of trees. The next causes of suppressed growth can lie in the burial of stems based on accumulated landslide material (Gärtner, 2007). As the landslide signal in this study, the abrupt growth suppression had to be at least approximately 50% compared with the mean tree-ring width of four previous tree rings (Schweingruber et al., 1990). Moreover, the intensity of abrupt growth suppression was evaluated and recorded according to the percentage decrease value into the two levels. Moderated abrupt growth suppression was defined as a 50–70% decrease, and strong abrupt growth suppression was defined as a 70% decrease in the tree-ring width. Next, the duration of such suppression must be detectable in at least eight subsequent tree rings (Stoffel and Corona, 2014).

Based on the identification of reaction wood and abrupt growth suppression, the activity of landslide movements was expressed by calculating the standard event-response (I_t) index following the formula of Shroder (1978) as

$$I_t = \frac{R_t}{A_t} \times 100 (\%) \quad (1)$$

where R is the number of trees with a growth disturbance in year t and A is the total number of sampled and analysed trees alive in year t . To prevent overestimation of values possibly causing false landslide events, two thresholds of the I_t index were defined (Stoffel et al., 2013). Probable landslide events were defined as years with I_t values between 5 and 10%, and certain events were defined as years with I_t values higher than 10% (Corona et al., 2014). Moreover, at least three trees had to simultaneously contain growth disturbances in their tree-ring series in the event year. The mentioned values of I_t thresholds were selected following the recommendation of Corona et al. (2014) based on the total number of

sampled and analysed trees on landslides (sample size). The frequency of detected past landslide events in each tree was expressed by the recurrence interval (R_i), which was calculated using the following formula:

$$R_i = \frac{A_s}{\sum L_s} \quad (2)$$

where A is the age of tree s and L is the total number of growth disturbances recorded in the tree-ring series of tree s . The calculated R_i values were subsequently spatially interpolated using the ordinary kriging method in Surfer9 software (Golden software, 2002).

4. Results

The geomorphic map was created as the first step of results processing. Next, a total of 53 trees (all *P. abies*) were sampled via 106 increment cores. The mean age of all the sampled trees was 80.6 years (stdev: 20.0 years), while the oldest trees were 107 years old and the youngest sampled tree was 34 years old.

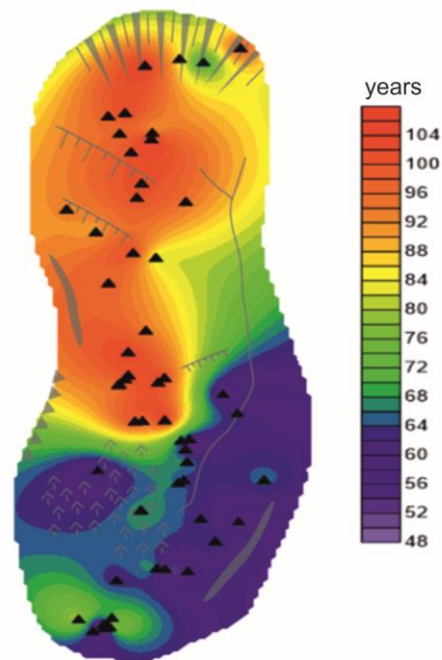


Figure 3 Spatial distribution of the tree age (black triangle – sampled tree)

The oldest trees were generally located in the zone below the main scarp, and their ages decreased towards the landslide front, where the

youngest trees were detected (Fig. 3). The intensity of stem tilting ranged between 1 and 26° (Fig. 4). The trees with a maximal intensity of stem tilting were located in three zones of the studied landslide surface. Trees occupying the rest of the landslide surface expressed moderate to low tilting intensity values. The most frequent direction of stem tilting was to SSW (19 trees).

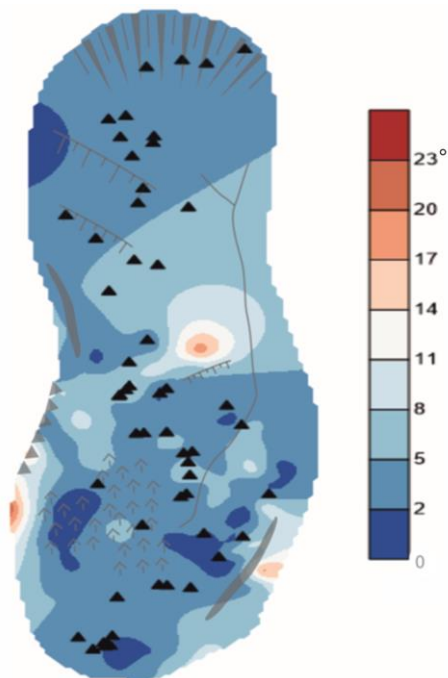


Figure 4 Spatial distribution of stem tilting direction (black triangle – sampled tree)

In general, the trees were most frequently tilted in the direction between W and S (77 trees) (Fig. 5). However, it seems that trees do not tend to cluster based on their tilting, and trees with various tilting directions are randomly dispersed across the entire landslide area. In total, 134 growth distributions (GD) were identified in all 106 tree-ring series. The occurrence of reaction wood dominated with 94 cases (70.1%) to abrupt growth suppression with 40 cases of occurrence (29.9%).

Each tree recorded 2.5 GD on average (stdev: 1.4 GD; minimum: one GD; maximum seven GD). The onsets of reaction wood occurred with a frequency of 1.8 cases per tree (stdev: 0.9 cases), and abrupt growth suppression occurred with a frequency of 0.8 cases per tree (stdev: 0.9 cases). The mild type of reaction wood dominated (75

cases; 79.8%) above the pronounced type (19 cases; 20.2%). The mean duration of reaction wood was 18.2 years (stdev: 17.5 years), with a minimal duration of two years and a maximum detected duration of 76 years. Strong reaction wood occurred in 11 trees in 1941, 1966 and 1997. Other years with the occurrence of strong reaction wood provided only one or two trees with this reaction wood type. Moderate abrupt growth suppression (GS) occurred in 29 cases (72.5%) and a strong intensity of GS occurred in 11 cases (27.5%). The maximal frequency of strong GS in one year was two cases.

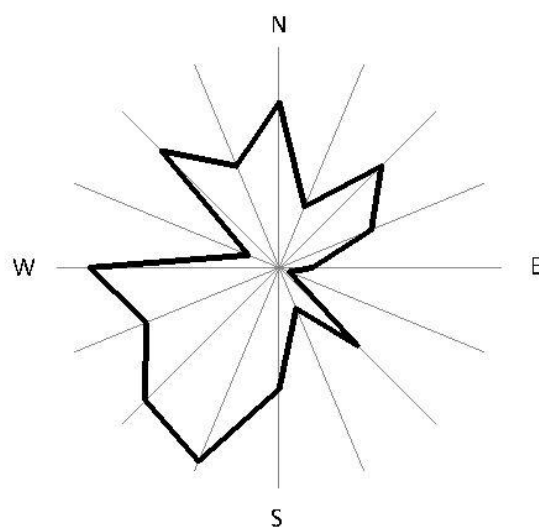


Figure 5 Graphical presentation of stem tilting direction frequency

The total chronology length covers the period of 91 years between 1927 and 2017. The oldest GD was recorded in 1927, when 26 sampled trees were alive. The youngest GD was detected in 2013. Reaction wood was recorded at a mean tree age of 29.2 years (stdev: 20.7 years) and abrupt growth suppression at a mean tree age of 52.6 years (stdev: 23.5 years). Based on the I_t index values, six years (1941, 1942, 1965, 1966, 1996, and 1997) can be assumed to be certain events of landslide movements with $I_t \geq 10\%$ (Fig. 6). The highest I_t values were reconstructed in 1997 (14 GD; $I_t=26.4\%$). The next highest I_t values were reached in 1966 (9 GD; $I_t=17.3\%$), 1941 (4 GD; $I_t=13.8\%$), 1965 (6 GD; $I_t=11.8\%$), 1996 (6 GD; $I_t=11.3\%$) and 1942 (3 GD; $I_t=10.3\%$). If we consider the probable events with I_t thresholds between 5 and 10%, the chronology of events increases by more than three times (Fig. 6). In total, 19

years can be supposed as event years with certain or probable events. The lowest I_t values were reached in 1953 (5.2%). The mean R_i value for each tree was 39.5 years (stdev: 19.9 years; minimal: 14.3 years; maximal: 101.0 years). The spatial interpolation of R_i values discovered the most and the least active landslide zones (Fig. 7). The zone of the main scarp and the landslide front expressed the highest frequency of past landslide events, and thus these are considered the most active. In contrast, the generally middle part of the landslide seems to be typical

with the lowest intensity of landslide activity. Based on the event-response maps (Fig. 8) in each certain event year, the spatial development of landslide activity can be observed. The first detected reactivation was located in the middle part of the landslide and in the zone below the main scarp. The second phase of movement between 1965 and 1966 shifted closer to the landslide front. Finally, the last detected events in 1996 and 1997 were localised exclusively in the front part of the landslide.

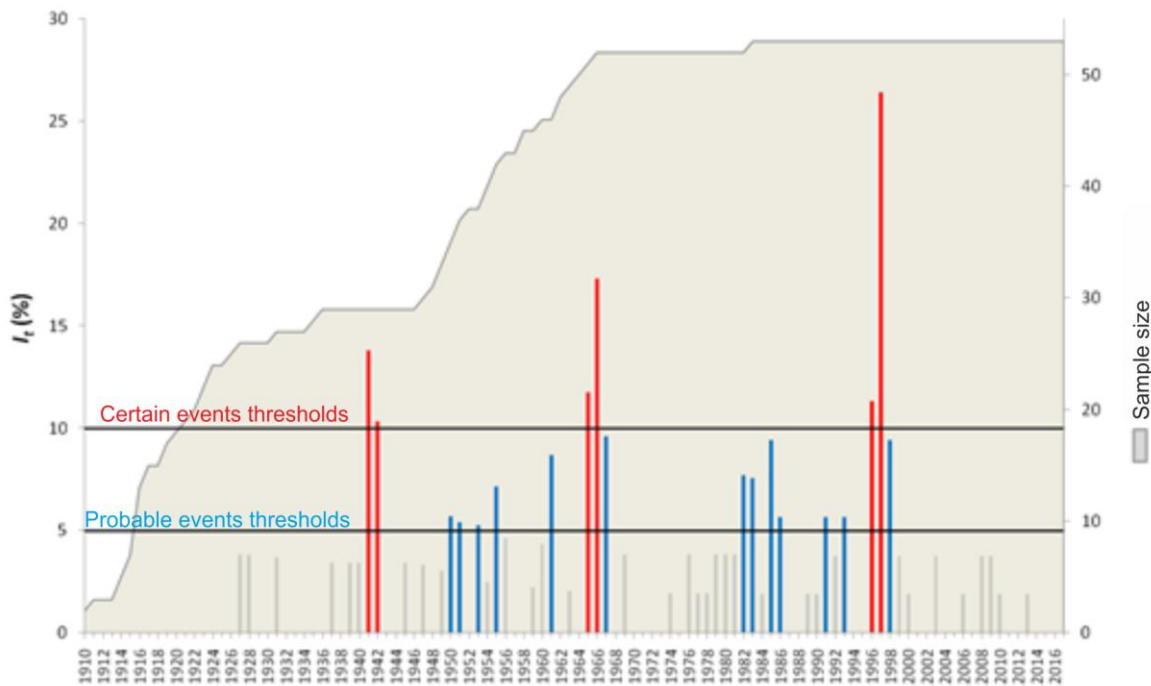


Figure 6 The chronology of dated landslide events ($I_t \geq 10\%$ – certain events; $10\% > I_t \geq 5\%$ – probable event)

5. Discussion

The flysch relief of the Outer Western Carpathians is a region with frequent occurrences of various slope deformations (Kirchner and Krejčí, 2002). Unfortunately, data about their past historical reactivations are extremely scarce or fully missing. The zones with the occurrence of ancient slope failures are the most frequently affected by new reactivations (Pánek et al., 2011).

This study helped with the collection of knowledge about past landslide activity in the case of the selected landslide close to the Jablůnka village in the Hostýnsko-Vsetínská highland, using dendrogeomorphic methods. Although the studied

landslide is located close to the inhabited area and thus possibly expresses a risk, no information about its reactivations or installed monitoring exists.

With the use of 106 increment cores from 53 disturbed trees (*P. abies*) occupying the studied landslide, the chronology of its past reactivation was created. The chronology was based on the identification of reaction wood and abrupt growth suppression. The presence of these GDs and tilted tree stems suggests the recent activity of the studied landslide (Stoffel and Bollschweiler, 2009). An important factor that could possibly affect GD creation is the age-dependent sensitivity of trees to landslide movements. According to Šilhán and Stoffel (2015), the ability of trees to record landslide signals in their

tree-ring series is highest between the ages of 60 and 70 years and the second peak is between 110 and 130 years. In the case of this study, the mean age when the recorded trees contained the onset of reaction wood was 29.2 years, but we used different tree species compared to the mentioned study. Moreover, the mean age of trees in this study was only 80.6 years. The very dispersed direction of stem tilting fully corresponds with the flow-like morphological character of landslides, when according to Šilhán (2021a), such a landslide does not tend to induce a one- or bi-modal distribution of stem tilting direction. Flow-like movements of landslides probably cause very irregular destabilization of the ground without any laws compared to landslide movements with rotational characteristics (Šilhán, 2015).

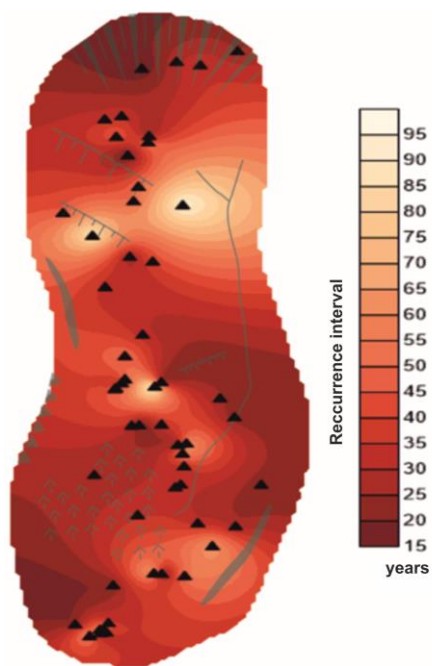


Figure 7 The spatial distribution of the recurrence interval of past landslide reactivations (black dot – sampled tree)

The I_t threshold for the landslide event definition was 5% for probable events for our sample size of 53 trees following the recommendation of Corona et al. (2014). Using this threshold enabled us to reconstruct the past 19 landslide event years (probable and certain) during the last 91 years. However, it is necessary to note that in eight cases, the detected events followed one another (e.g., 1941 and 1942 or 1950 and 1951). In contrast, when

the I_t threshold was increased to 10%, the number of detected events decreased to six cases, but all of them were grouped in pairs. Such a detected chronology can suggest the specific behaviour of the landslide body when the reactivation can be strong enough to have some inertia or can be followed by the next minor events even several months after its initiation. This assumption even corresponds with the observation of Krejčí et al. (2002) after the landslide calamity in 1997, when the secondary reactivations occurred even several months after the main landslide phase in the studied region. A case with such a situation is, for instance, in 1941 with the occurrence of a strong type of reaction wood and the following year (1942) with the occurrence of a mild type of reaction wood. For instance, Stoffel and Corona (2014) suggest using the occurrence of reaction wood with a weak intensity only for verification of events, but not for direct dating. The other dated event years are typical of the initial occurrence of reaction wood with a mild intensity followed by the event year detected by reaction wood with a strong intensity. Thus, the occurrence of landslide events at the turn of the vegetation period can be expected. Comparing the results of dating in this study with results published by Šilhán (2021b) from the wider region, event years are confirmed to be 33.3%. Nevertheless, when considering even probable events, the agreement with landslide events in the wider region reaches 42.1%. It is well known that GDs in the form of compression tree and abrupt growth suppression exhibit a certain measure of inertia and therefore cannot be used to date annual landslide events within a tree-ring series of a single tree (Stoffel and Corona, 2014). Thus, the aforementioned successive event years were always reconstructed from different trees, which allowed the detection of recurrent events.

Unfortunately, the dendrogeomorphic approach used could not distinguish whether several recurrent landslide movements occurred during one event year. Thus, it is even possible and likely that landslide movements were repeated in an event year, but tree-ring based methods only captured one event year at a time.

Another important aspect of dendrogeomorphic dating of landslides is the possible delay in GD for-

mation (Stoffel and Bollschweiler, 2009), which is especially true for abrupt growth release (Chalupová et al., 2020), but was not used in this study. Nevertheless, the influence of this factor on the resulting chronology cannot be completely ruled out. However, the number of trees with delayed GD is not

very high (Šilhán, 2017), and thus, due to the high number of trees with GD in consecutive years, it can be attributed to real recurrent landslide events. This behaviour for landslides in the study region has been noted by Kirchner and Krejčí (2002).

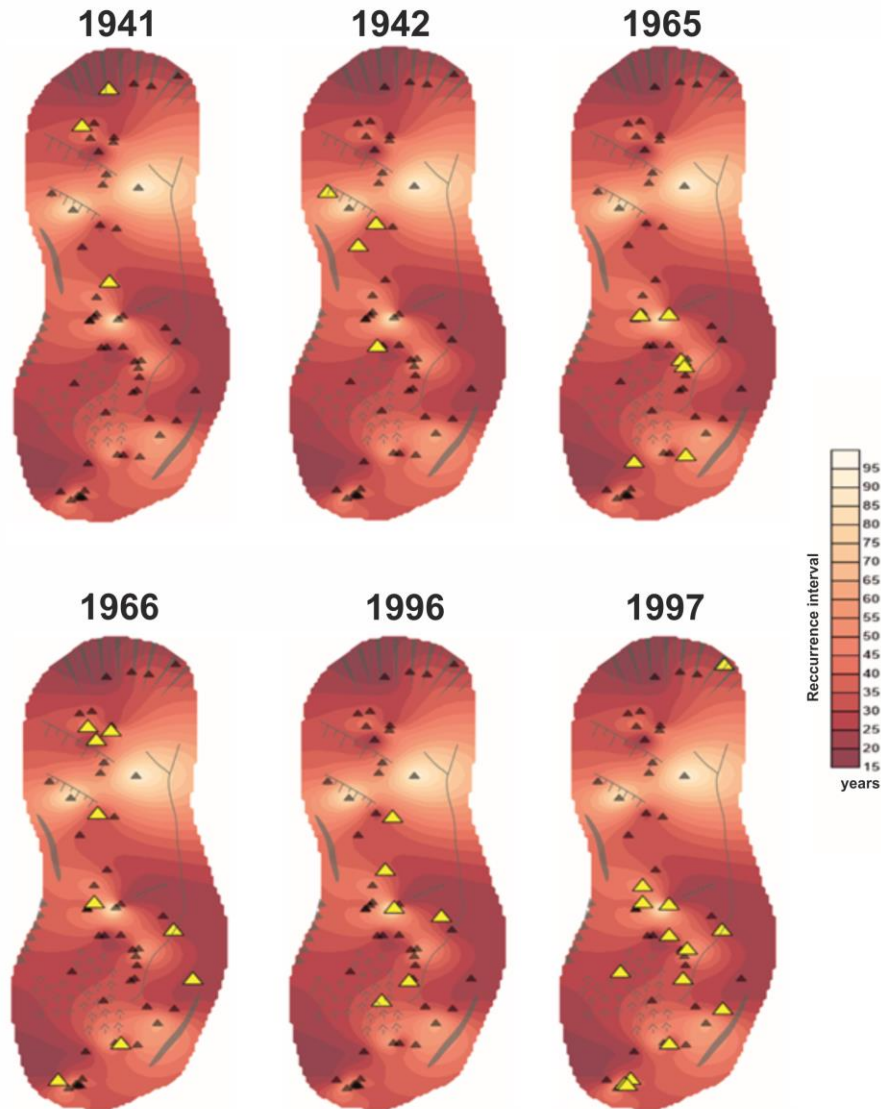


Figure 8 Event-response maps in certain individual event years (yellow dot – tree with GD, black dot – sampled tree without GD)

The reconstructed development of landslide re-activations from event-response maps (Fig. 8) corresponds to the spatial distribution of the recurrence interval (Fig. 7) and field observations in the zone of the landslide front, where the activity of landslide movements can be assumed to be the highest. This zone is simultaneously covered by the youngest

trees (40–60 years). Such an age structure could lead to an increased sensitivity of trees in this zone to landslide movements. In contrast, the zone of the main scarp is typical of the presence of low recurrence intervals and older trees. Thus, the age structure of trees and the different sensitivities of trees

could affect the reconstruction results (Šilhán and Stoffel, 2015).

The last year with the detected landslide event was 1997 and there was a probable landslide event in 1998. No other years with I_t values higher than 5% were detected after these two years. Moreover, no strong type of reaction wood or strong abrupt growth suppression was detected in this period. As the occurrence of most cases of strong reaction wood occurred in years defined as a certain event, it is possible to suggest that the landslide activity in the recent period after 1996 was minimal. Although no analysis of triggers was performed in this study, the dated years suggest a strong effect of extreme precipitation on landslide reactivation. For instance, 1940, 1996, and 1997 are well known for this (Štekl et al., 2001). Thus, future studies should focus on a comparison of dated landslide events with hydro-meteorological extremes.

6. Conclusions

This study represented chronological data (based on dendrogeomorphic research) of landslide reactivation from the extended area of Jablůnka village in the Hostýnsko–Vsetínská highland during the period between 1927 and 2017. The reconstruction was performed using data from 106 increment curves from 53 disturbed individuals of *P. abies*. Two I_t thresholds were used for the past landslide event definition. In general, six certain and 13 probable landslide reactivations were detected. The mean recurrence interval of landslide reactivations was 39.5 years, and the most active landslide zones were detected in the area of the landslide front and main scarp. Recently, landslides seem to be stable after the last certain event in 1997, which was highly likely triggered by extreme precipitation totals.

Acknowledgements

The Czech Science Foundation project 22-12522S and the University of Ostrava project no. SGS02/PřF/2019–2020 supported this study. The language was reviewed by the American Journal Experts. David Řeha, Matěj Kaloč and Radek Tichavský are warmly acknowledged for their help with the field work.

References

- Alestalo J. 1971. Dendrochronological interpretation of geomorphic processes. *Fennia* **105**: 1–139.
- Baillie MGL. 2008. Proposed re-dating of the European ice core chronology by seven years prior to the 7th century AD. *Geophysical Research Letters* **35**: L15813.
- Ballesteros JA, Bodoque JM, Díez-Herrero A, Sanchez-Silva M, Stoffel M. 2011. Calibration of floodplain roughness and estimation of flood discharge based on tree-ring evidence and hydraulic modelling. *Journal of Hydrology* **403**: 103–115.
- Bíl M, Krejčí O, Bílová M, Kubeček J, Sedoník J, Krejčí V. 2014. A chronology of landsliding and its impacts on the village of Halenkovice, Outer Western Carpathians. *Geografie* **119**(4): 342–363.
- Bollschweiler M, Stoffel M, Vazquez Selem L, Palacios D. 2009. Tree-ring reconstruction of past lahar activity at Popocatepetl volcano, Mexico. *Holocene* **20**: 265–274.
- Chalupová O, Šilhán K, Kapustová V, Chalupa V. 2020. Spatiotemporal distribution of growth releases and suppressions along a landslide body. *Dendrochronologia* **60**: 125676.
- Chandler J. 1999. Effective application of automated digital photogrammetry for geomorphological research. *Earth Surface Processes and Landforms* **24**: 51–63.
- Corona C, Lopez Saez J, Stoffel M. 2014. Defining optimal sample size, sampling design and thresholds for dendrogeomorphic landslide reconstructions. *Quaternary Geochronology* **22**: 72–84.
- Corominas J, Moya J. 2008. A review of assessing landslide frequency for hazard zoning purposes. *Engineering Geology* **102**: 193–213.
- Gärtner H. 2007. Glacial landforms, tree rings – Dendrogeomorphology. In: Elias PP (ed.) *Encyclopedia of Quaternary Science*. University of London, 979–988.
- Golden Software. 2002. Surfer Version 8 – Reference Manual, Golden Software Inc., CA, USA.
- Holmes RL. 1994. *Dendrochronology program manual. Laboratory of Tree-Ring Research*. Tucson, Arizona, USA.
- Jacoby GC, Sheppard PR, Sieh KE. 1988. Irregular recurrence of large earthquakes along the San Andreas fault: evidence from trees. *Science* **241**: 196–199.
- Kirchner K, Krejčí O. 2002. Slope deformations and their significance for relief development in the middle part of the Outer Western Carpathians. *Moravian Geographical Reports* **10**: 10–19.
- Kirchner K, Krejčí O, Máchka Z, Bíl M. 2000. Slope deformations in eastern Moravia, Vsetín District (Outer Western Carpathians). *Acta universitatis Carolinae* **35**: 133–143.

- Kirchner K, Lacina J. 2004. Slope movements as a disturbance agent increasing heterogeneity and biodiversity of landscape in eastern Moravia. *Ekológia* **23**: 94–103.
- Klimeš J, Rowberry MD, Blahůt J, Briestenský M, Hartvich F, Košťák B, Rybář J, Stemberk J, Štěpančíková P. 2012. The monitoring of slow-moving landslides and assessment of stabilisation measures using an optical-mechanical crack gauge. *Landslides* **9**: 407–415.
- Krejčí O, Baroň I, Bíl M, Jurová Z, Bárta J, Hubatka F, Kašpárek M, Kirchner K, Stach J. 2002. Some examples of deep seated landslides in the flysch Belt of the Western Carpathians. *Landslides – Proceedings of the First European Conference on Landslides*, Prague, Czechia, 373–380.
- Lopez-Saez J, Corona C, Stoffel M, Astrade L, Berger F, Malet JP. 2012a. Dendrogeomorphic reconstruction of past landslide reactivation with seasonal precision: the Bois Noir landslide, southeast French Alps. *Landslides* **9**(2): 189–203.
- Lopez Saez, Corona C, Stoffel M, Schoeneich P, Berger F. 2012b. Probability maps of landslide reactivation derived from tree-ring records: Pra Bellon landslide, southern French Alps. *Geomorphology* **138**: 189–202.
- Menčík E, et al. 1983. *Geologie Moravskoslezských Beskyd a Podbeskydské pahorkatiny*. Ústřední Ústav Geologický, Praha.
- Pánek T, Šilhán K, Tábořík P, Hradecký J, Smolková V, Lenart J, Brázdil R, Kašičková L, Pazdur A. 2011. Catastrophic slope failure and its origins: case of the May 2010 Girová Mountain long-runout rockslide (Czech Republic). *Geomorphology* **130**: 352–364.
- Schweingruber FH, Eckstein D, Serre-Bachet F, Bräker OU. 1990. Identification, presentation and interpretation of event years and pointer years in dendrochronology. *Dendrochronologia* **8**: 9–38.
- Shroder JF. 1978. Dendrogeomorphological analysis of mass movement on Table Cliffs Plateau, Utah. *Quaternary Research* **9**: 168–185.
- Šilhán K. 2015. Can tree tilting indicate mechanism of slope movement? *Engineering geology* **199**: 157–164.
- Šilhán K. 2017. Evaluation of growth disturbances of *Picea abies* (L.) Karst. to disturbances caused by landslide movements. *Geomorphology* **276**: 51–58.
- Šilhán K. 2020. Dendrogeomorphology of landslides: principles, results and perspectives. *Landslides* **17**: 2421–2441.
- Šilhán K. 2021a Dendrogeomorphology of different landslide types: a review. *Forests* **12**: 261.
- Šilhán K. 2021b Regional activity of flow-like landslides in the Outer Western Carpathians: dendrogeomorphic spatio-temporal reconstruction. *Dendrochronologia* **67**: 125830.
- Šilhán K, Stoffel M. 2015. Impacts of age-dependent tree sensitivity and dating approaches on dendrogeomorphic time series of landslides. *Geomorphology* **236**: 34–43.
- Štekl J, Brázdil R, Kakos V, Jež J, Tolasz R, Sokol O. 2001. *Extrémní denní srážkové úhrny na území ČR v období 1879–2000 a jejich synoptické příčiny*. Praha, Národní klimatický program 31.
- Stoffel M, Bollschweiler M. 2009. What Tree Rings Can Tell About Earth–Surface Processes: Teaching the Principles of Dendrogeomorphology. *Geography Compass* **3**(3): 1013–1037.
- Stoffel M, Wilford DJ. 2012. Hydrogeomorphic processes and vegetation: disturbance, process histories, dependencies and interactions. *Earth Surface Processes and Landforms* **37**: 9–22.
- Stoffel M, Corona C. 2014. Dendroecological dating of geomorphic disturbance in trees. *Tree-ring research* **70**(1): 3–20.
- Stoffel M, Butler DR, Corona C. 2013. Mass movements and tree rings: A guide to dendrogeomorphic field sampling and dating. *Geomorphology* **200**: 106–120.
- Stoffel M, Conus D, Grichting MA, Lièvre I, Maître G. 2008. Unraveling the patterns of late Holocene debris-flow activity on a cone in the Swiss Alps: chronology, environment and implications for the future. *Global and Planetary Change* **60**: 222–234.
- Stokes M, Smiley M. 1968. *An Introduction to Tree-Ring Dating*. The University of Chicago Press.
- Timell TE. 1986. *Compression wood in gymnosperms*. Berlin, Germany, Springer.
- Tolasz R, Brázdil R, et al. 2007. *Climate atlas of Czechia*. Czech Hydrometeorological Institute, Praha.
- Van den Eeckhaut M, Hervás J. 2012. State of the art of national landslide databases in Europe and their potential for assessing landslide susceptibility, hazard and risk. *Geomorphology* **139–140**: 545–558.
- V.I.A.S. 2005. *Vienna Institute of Archaeological Science. Time Table. Installation and instruction manual*, ver. 2.1, Vienna.
- Wang G. 2011. GPS Landslide Monitoring: Single Base vs. Network Solutions – A case study based on the Puerto Rico and Virgin Islands Permanent GPS Network. *Journal of Geodetic Science* **1**(3): 191–203.
- Westing AH. 1965. Formation and function of compression wood in gymnosperms II. *Botanical Reviews* **34**: 51–78.
- Zhang Y, Stoffel M, Liang E, Guillet S, Shao X. 2019. Centennial-scale process activity in a complex landslide body in the Qilian Mountains, northeast Tibetan Plateau, China. *Catena* **179**: 29–38.

Seasonal and spatial variability of the morphodynamics of slopes within snow avalanche starting zones in the Tatra Mountains

Zofia RĄCZKOWSKA^{1*}, Elżbieta ROJAN²

¹Department of Geo-environmental Research, Institute of Geography and Spatial Organization, Polish Academy of Sciences, Św. Jana 22, 31–018 Kraków, Poland

²Department of Geomorphology, Faculty of Geography and Regional Studies University of Warsaw, Krakowskie Przedmieście 30, 00–927 Warsaw, Poland

Received 31 January 2022; Revised 19 December 2022; Accepted 19 December 2022

*Correspondence to: Zofia RĄCZKOWSKA; e-mail: raczk@zg.pan.krakow.pl

ABSTRACT

The paper aims to examine the morphodynamics of slopes within snow avalanche starting zones in the Tatras. The analysis of morphodynamics is based on the results of a four-year programme of monitoring of slope surface changes at 8 study sites. It is focused on the comparison of slope activity in the winter and summer seasons. The results of the study were examined taking into consideration the meteorological conditions during the study period and the relief. It was found that relief in the Tatras favours the occurrence of snow avalanches. In the period without snow avalanches, secular morphogenetic processes modified slopes within the snow avalanche starting zones. As a result, the slope cover material was triggered and moved in a chaotic and random manner as well as accumulating. The sites of erosion and accumulation of material are varied in time and space within the snow avalanche starting zones. Generally, erosion is the main effect of secular morphogenetic processes.

KEYWORDS Snow avalanche starting zone; Slope morphodynamic; Seasonal differentiation; Spatial differentiation; Tatra Mountains

1. Introduction

Snow avalanches are a significant element of high-mountain denudational systems. Their starting zones are usually located in the uppermost parts of valley slopes. The morphological features of the

starting zones strongly influence the size and type of snow avalanches (McClung and Schaerer, 2006). However, the activity of snow avalanches manifests itself in mountain slope morphology (e.g. Rapp,

1960; Luckman, 1978; Becht, 1995; Kotarba, 2002; Hreško et al., 2005; Sas et al., 2010; Lempa et al., 2015). Erosional landforms in the starting zones of snow avalanches indicate that erosion predominates there, mostly on soil-mantled slopes, although erosion was also evidenced in an avalanche starting zone situated on bedrock (Moore et al., 2013).

It was also found that the activity of avalanches in the Tatra Mountains manifests itself in the slope morphology of the avalanche starting zone in forms of erosional landforms (Rączkowska et al., 2016a; Gądek et al., 2017). Kotarba (1976) and Hreško et al. (2005) indicated that, as a result of full-depth avalanches in the avalanche starting zone (the upper part of the avalanche path), soil destruction dominates and creates favourable conditions for consecutive processes, such as nivation, cryogenic processes, deflation and erosion. The average values of surface lowering due to avalanche activity in the Tatras, range from several dozen to 350 mm during a single event (Stankoviansky and Midriak, 1998). One avalanche can transport several hundred kilograms, occasionally over a tonne of rock debris (Kłapa, 1980).

In the Tatra Mountains avalanches originate in the areas above the upper timberline (Rączkowska et al., 2016a), where processes related to the periglacial climate (Jahn, 1958, 1975) and slope alluviation (Kotarba, 1976, 1996; Midriak, 1996; Rączkowska, 1999) are prevalent. According to Kłapa (1980), based on many years of research, avalanche activity predominantly occurs in the nival season, one of the four morphogenetic seasons distinguished in the Tatras. The subsequent nivopluvial season, which is characterised by a rich set of geomorphological processes, is the most active in terms of the dynamics of the processes throughout the year. In turn, the pluvial season can be considered both as active and very active, depending on the type of summer, and especially on the occurrence of extreme rainfall.

Avalanches are among the rapid mass movements active in the winter half of the year, while in the summer half of the year slope morphodynamics are driven by rainfall induced processes. The modern development of slopes within avalanche starting zones is the result of full-depth avalanches and

other secular morphogenetic processes which determine change throughout the year. The share of these two types of process can vary over time.

The aim of the study is to examine the morphodynamics of slopes within the starting zones of avalanches in the Tatra Mountains, with particular attention to its differentiation between winter and summer seasons. It is based on the results of a four-year programme of monitoring of slope surface changes.

2. Study area

The Tatra Mountains form the highest range in the Carpathians, rising to 2655 m a.s.l. (Gerlachovský štít). The area is divided into the Western Tatras, the High Tatras and the Belianske Tatras. They are formed of a crystalline core built of granites and metamorphic rocks, rimmed with sedimentary rocks to the north (Nemčok et al., 1994; Piotrowska et al., 2015). The Tatra Mountains were glaciated in the Pleistocene which has resulted in an alpine character to their relief (Klimaszewski, 1988; Rączkowski et al., 2015).

The mean annual air temperature (MAAT) ranges from 2°C to about -4°C on the highest peaks (Hess, 1965; Konček ed., 1974; Žmudzka et al., 2015). The mean total precipitation ranges from about 1100 mm in the northern foothills to over 2000 mm on the highest parts, yet the highest precipitation occurs in the 1500–1900 m a.s.l. zone. The number of days with seasonal snow cover ranges from about 100 to over 220 (Ustrnul et al., 2015).

The study slopes are located within the snow avalanche starting zones, which in the Tatra Mountains are found at altitudes of 1142–2620 m a.s.l. in the alpine and subalpine zones. The size of the avalanche starting zones varies in size from 312 to 198,942 m². They are largest in the Western Tatras, where their area is 28,593 m² on average. Approximately 90% of the avalanche starting zones in the Tatra Mountains include 26–55° slopes (Rączkowska et al., 2016b).

The study of the slope morphodynamics within the avalanche starting zones was carried out on eight selected couloirs. Their location is shown in Figure 1. These couloirs were purposely selected to include the northern and southern slopes of the Ta-

tra Mountains and some slopes of eastern and western exposure. Table 1 contains the most important geological and morphometric features regarding the avalanche starting zones studied, and Figure 2 presents their altitudinal location. The starting zones studied differ in slope character and li-

thology. Layers of Quaternary sediments cover slopes on the Žleb Žandarmerii and the Osterva study sites, and rocky slopes lie on the Dwoisty Žleb and Malá Bašta. The slope inclination is mostly similar, varying between 30–47° in the Western Tatra and 40–67° in the High Tatra.

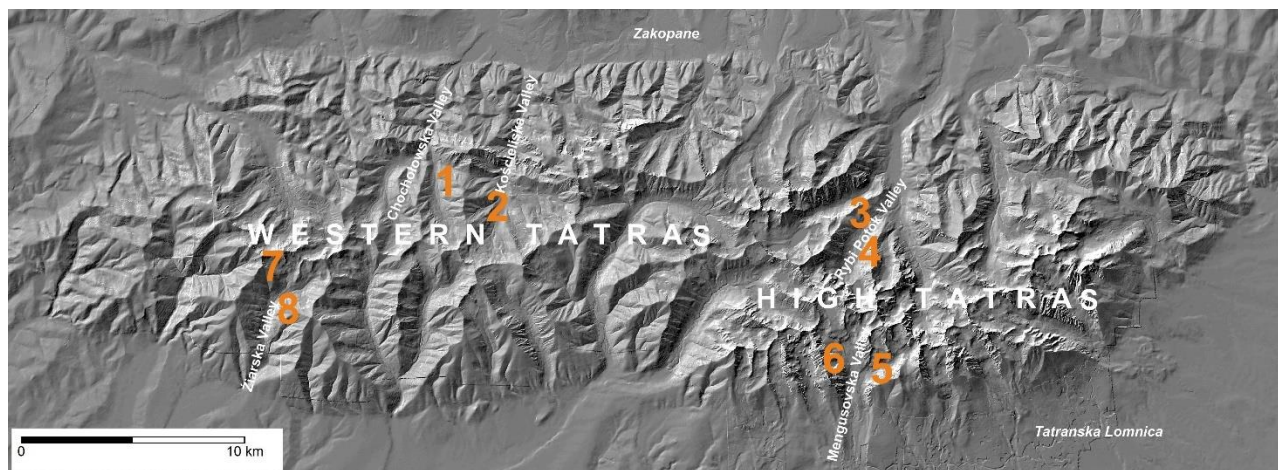


Figure 1 Location of the study sites marked by numbers. Their characteristics are in Table 1

Table 1 Characteristics of study sites (No. – number in Fig. 1)

	Location of the study site		Lithology (after Nemčok et al. 1994)	Slope type	Slope [°]	Aspect
1	Western Tatra, Chochołowska Valley	Pośredni Žleb	gneisses, migmatites	debris mantled slope	31–47	W
2	Western Tatra, Kościeliska Valley	Ornaczański Žleb	gneisses, migmatites	debris mantled slope	30–47	E
3	High Tatra, Rybi Potok Valley	Žleb Žandarmerii	biotite to two-mica granodiorites to granites, Quaternary sediments	debris mantled slope	45–67	E
4	High Tatra, Rybi Potok Valley	Dwoisty Žleb	biotite to two-mica granodiorites to granites	rocky slope	40–47	W
5	High Tatra, Mengusovská Valley	Ostrva	Quaternary sediments, biotite tonalites to granodiorites	debris mantled slope	45–67	W
6	High Tatra, Mengusovská Valley	Malá Bašta	biotite tonalites to granodiorites	rocky slope	45–67	E
7	Western Tatra, Žiarska Valley	Príslop	micaschists, gneisses, biotite to two-mica granodiorites to granites	debris mantled slope	40–47	SE
8	Western Tatra, Žiarska Valley	Baranec	micaschists, gneisses, migmatites	debris mantled slope	40–47	NW

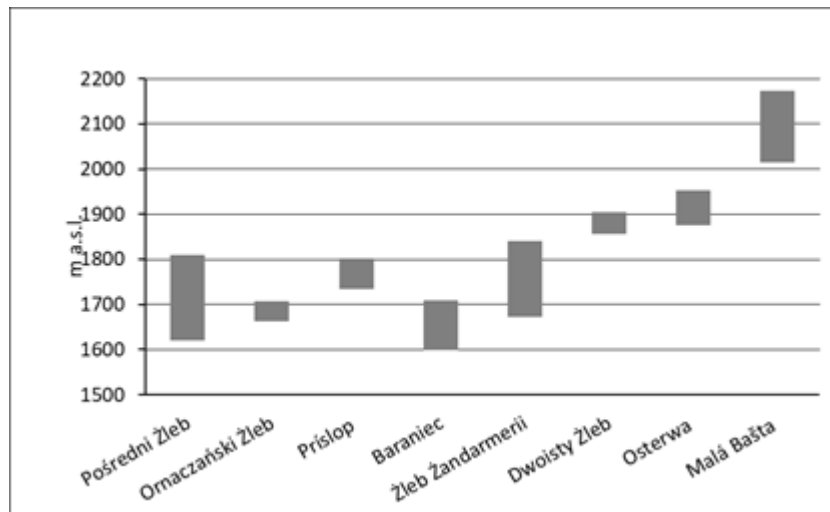


Figure 2 Altitudinal range of the study areas within the particular starting zone

3. Materials and methods

The size and direction of changes in the relief of the surfaces of the avalanche starting zones was determined using benchmarks. These benchmarks were steel pipes with a diameter of 1.27 cm and a length of 0.5 m (Fig. 3). They were installed within the erosional scars at each of the snow avalanche starting zones selected for study (Table 1, Fig. 4).



Figure 3 An example of benchmark and method of measurement

In total, 49 benchmarks were installed across the Tatras. The number of benchmarks in individual snow avalanche starting zones was from 3 to 10 (Table 2, Fig. 4).

The study sites were mainly placed in the central and lower parts of the avalanche starting zones, distributed along their cross section. Erosional scars and niches usually develop in those parts of the ava-

lanche starting zones, while they are less often found in their upper areas (Figs. 4 and 5).

The study was conducted in the years 2012–2016, comprising four winter periods and three summer periods. During the study period, however, there were no full-depth avalanches at any of the sites. The height of the pipe above the ground was measured at each benchmark (Fig. 3). The measurements were carried out twice a year – after the winter (once the snow had melted, usually in June) and after the summer (before snowfall, usually in October). In total, 126 measurement results were obtained.

Table 2 Number of benchmarks at study sites

Area	Study site	Number of benchmarks
High Tatras	Žleb Žandarmerii	6
	Dwoisty Żleb	3
	Malá Bašta	8
	Ostrva	4
Western Tatras	Pośredni Żleb	5
	Ornaczański Żleb	9
	Príslop	10
	Baranec	4
Tatras	Total	49

On the basis of the differences between the measurements of the two periods – summer and winter, the seasonal or annual variability of lowering or accretion of the slope surface at the observation

sites can be determined. It was assumed that results with a negative value indicate a loss of soil from the slope, i.e. the predominance of erosion. Results with positive values indicate the supply of material,

meaning the predominance of accumulation. The number of cases and their percentage were the basis for the assessment.

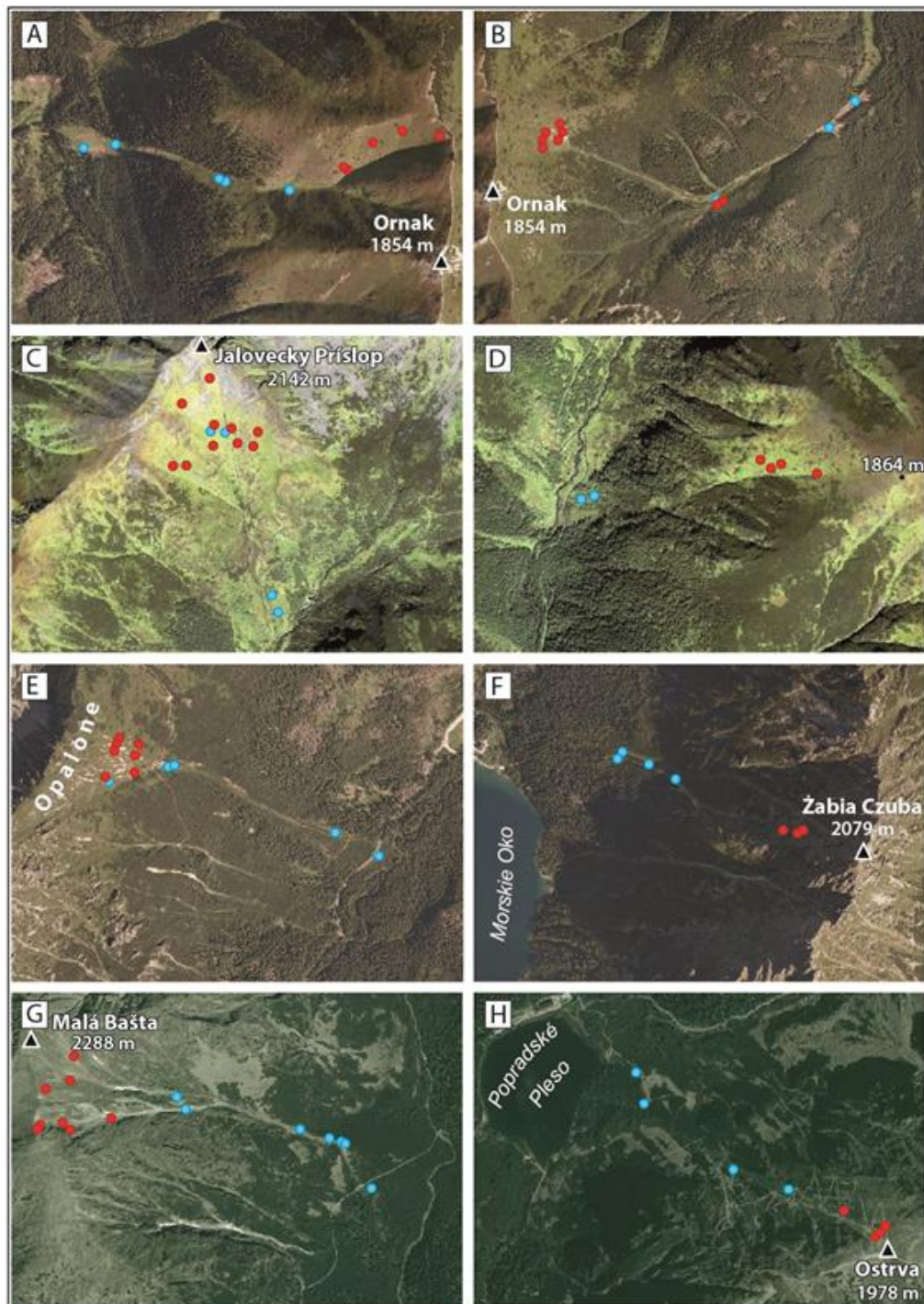


Figure 4 Location of the measurement points within the snow avalanche tracks. Red dots –steel pipes, blue dots – other benchmarks; A – Pośredni Żleb (1), B – Ornaczański Żleb (2), C – Przysłop (7), D – Baranec (8), E – Żleb Żandarmerii (3), F – Dwoisty Żleb (4), F – Malá Bašta (5), G – Ostrva (6), the number in bracket corresponds to the number of the study site in Figure 1

The meteorological conditions during the research period were determined using data from the Station of the Institute of Meteorology and Water Management at Hala Gąsienicowa, located at an altitude of 1520 m a.s.l. in the Polish section of the Tatras (<https://danepubliczne.imgw.pl/>). The data on daily precipitation and daily air temperature were used.

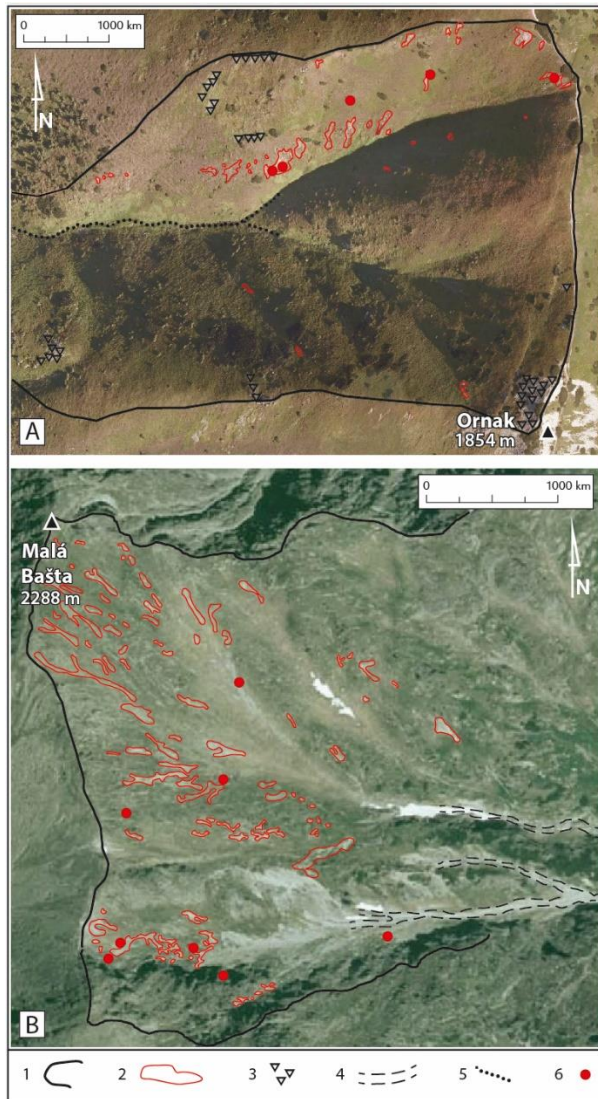


Figure 5 An examples of the snow avalanche starting zones. A – Pośredni Żleb study site in the Western Tatras, the slopes are mantled with compact covers of regolith and vegetation. B – Malá Bašta study site in the High Tatras, the rock slopes are bare or sparsely covered with regolith and vegetation; 1 – boundary of snow avalanche starting zone, 2 – erosional scars, 3 – blockfield, 4 – debris flow gully, 5 – initial channel, 6 – benchmark

Additionally, the fractional composition of the slope covers was determined at study sites in the Polish section of the Tatras. Soil samples were collected from each of the four study sites there. The number of samples varied from 3 to 5 at individual sites. The grain-size composition of the soil samples was determined using a combined sieving method and a Malvern laser particle-sizer (<2 mm).

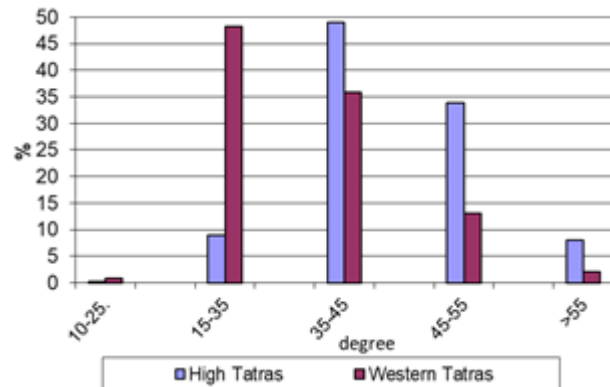


Figure 6 Inclination of slopes within the avalanches starting zones

4. Results

4.1 The morphological characteristics of snow avalanche starting zones

Starting zones are usually located on the source areas of rocky chutes and couloirs at an altitude 1697–1856 m a.s.l. in the Western Tatras and 2022–2101 m a.s.l. in the High Tatras (Table 3). They differ in size and morphology. These forms are much larger, but with lower slope inclination, in the Western Tatras (Fig. 6). According to McClung and Schaerer (2006) such an inclination (20–35°) favours the occurrence of slab and loose wet avalanches. These are mostly on debris mantled slopes covered by vegetation. In the High Tatras the slopes within the starting zones are often areas with bare and rocky surface and a very variable inclination that favours not only slab (30–45°) but also dry (30–60°) and cascade avalanches (60–90°).

The erosional scars in the avalanche starting zones are characteristic landforms developed due to avalanche erosion combined with sheep grazing in the Tatras (Rączkowska et al., 2016b; Gądek et al., 2017). They differ in number and size in individual starting zones.

Table 3 Characteristics of snow avalanche starting zones

Region	Upper limit (m a.s.l.)			Lower limit (m a.s.l.)			Area of starting zone (m ²)		
	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean
Western Tatras	2228	1301	1856	2085	1157	1697	198942	755	28593
High Tatras	2620	1222	2101	2587	1142	2022	194365	312	6971

4.2 Grain-size composition of the study sites

The results of the analysis of soil samples show that they are mostly composed of a sand fraction, however finer material is also present (Fig. 7). There is no distinct difference found between the study sites in the High Tatras and the Western Tatras, and also there are very few differences found between individual study sites. Although the presence of fine material in the grain-size composition of soil indicates that there is material which can be easily triggered and moved.

4.3 Meteorological conditions

During the study period, meteorological conditions varied between individual winter and summer seasons respectively (Figs. 8 and 9).

Thermal and humidity conditions during the winters of the study period are characterised by relatively low precipitation and high variability of temperature (Fig. 8). Generally, precipitation was rather low. Heavy precipitation only occurred on two occasions, but of a different character. The temperature frequently fluctuated around freezing. This resulted in a fluctuation of the presence of snow cover and its short duration. This discontinuity in snow cover presence was especially noted in the winter of 2013/2014.

The 2014 summer season was more humid regarding both the persistence and totals of precipitation (Fig. 9). There were few daily totals higher than 30 mm, which are considered extreme events (Niedźwiedź et al., 2015) which could even have triggered debris flows (Kotarba, 1992).

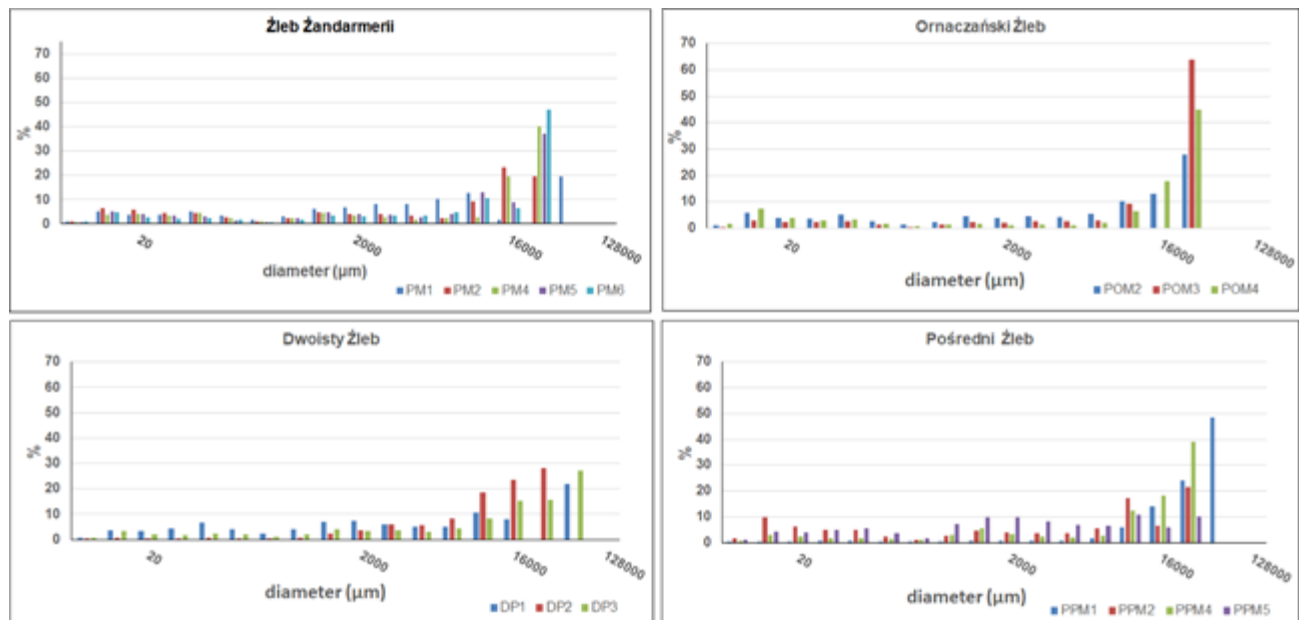


Figure 7 Differentiation of grain-size composition of soils on slopes within the snow avalanche starting zones in the Polish part of the Tatras. PM1–PM6, POM2–POM4, DP1–DP3, PPM1–PPM5 marks soil sample number

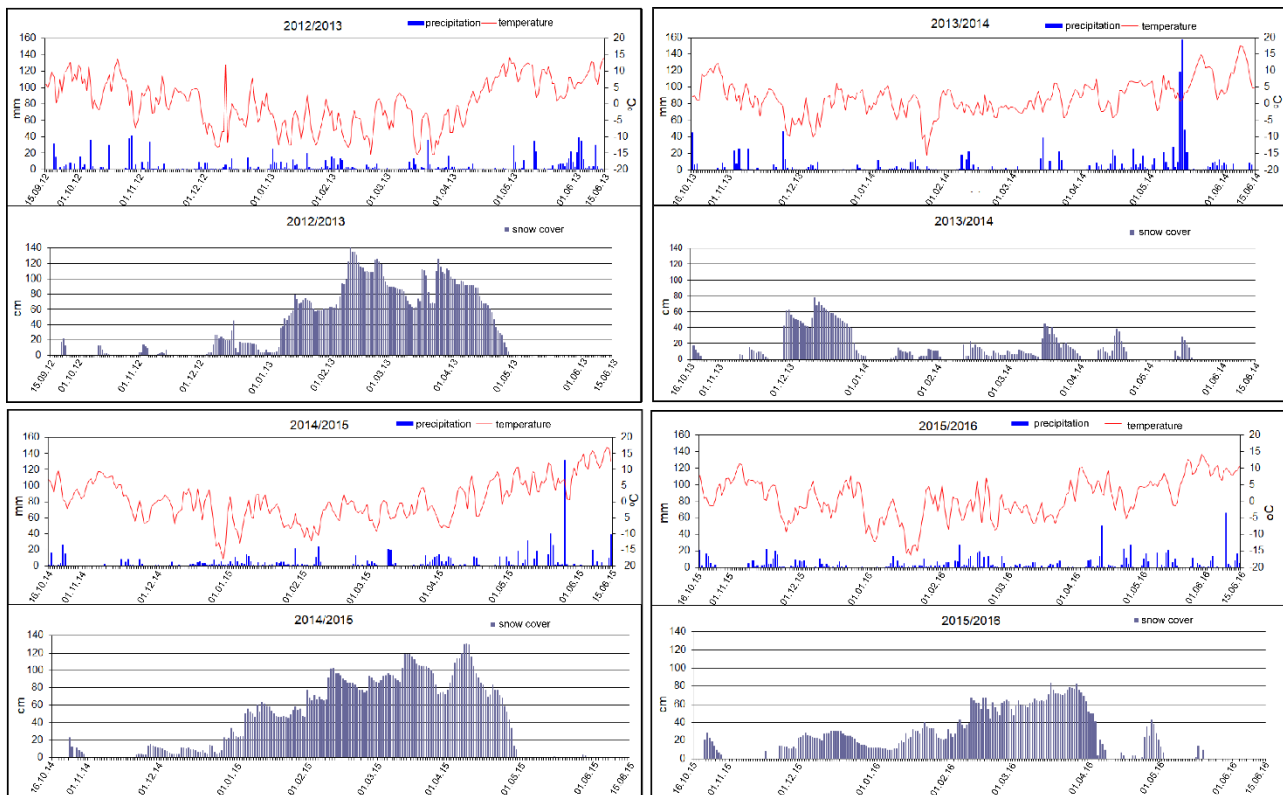


Figure 8 Meteorological conditions in the winter seasons during study period

Table 4 Changes of slope surface in studied starting zones in period 2012–2016

	Żleb Żandarmerii	Dwoisty Żleb	Ostrva	Malá Bašta	Pośredni Żleb	Ornaczański Żleb	Przysłop	Baranec
Erosion [%]*	50	66,7	100	50	80	80	78	100
Accumulation [%]*	50	33,3	0	25	0	20	22	0
No changes [%]*	0	0	0	25	20	0	0	0
Min** [cm]	-0,3	0,1	-1,4	0	0	-0,7	-0,2	-3,4
Max ** [cm]	4	-1,0	-4,5	-4,7	-7,0	6,6	-5,8	-6,2

* % of the total number of benchmarks in particular study site (couloir) ** difference in cm between the first and last measurement

4.4 Morphodynamic changes of the slope surface in snow avalanche starting zones

Significant variety appears between particular study sites when discussing slope activity during the four-year study period (Table 4). Lowering of the slope surface due to erosion occurred very frequently. It was found in 50 to 100% of measurements. Slope

accretion was found in far fewer measurements, and it was not even found at all at three study sites. There is also a large variation in the magnitude of the changes found in individual measurements. The changes range from 0 cm to 7 cm. In the winter season erosion prevails in six of the eight starting zones

studied, while accumulation prevails in only two of them (Fig. 10). The highest number of erosion events (>70% of measurements) was found in the Ostrva, Baranec and Prislop study sites located on southern slopes of the massif. These slopes are generally warmer and snow melted earlier there than on the northern slopes of the massif. The slope surface is affected by cryogenic processes and erosion by meltwater and rainwater.

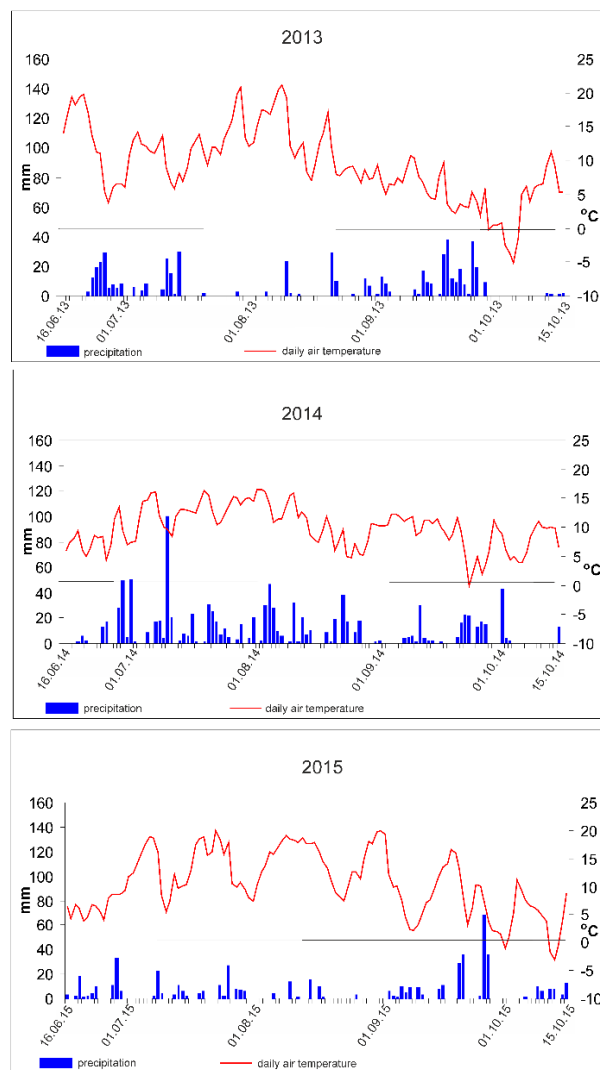


Figure 9 Precipitation and temperature conditions in summer seasons during study period

Two starting zones, where accumulation prevails, are located in the High Tatras at high altitude on the northern slopes of the massif, which favours the longer persistence of snow cover. Hence, the material accumulated in the traps formed in those places where the snow cover and the ground freeze

is preserved because it is exposed to erosion by rainwater for a shorter period.

Erosion prevails in the avalanche starting zones in the summer seasons, except for the Ostrva and the Prislop study sites where accumulation is equally or slightly more frequent (Fig. 10). Erosion was found in 20 to 90 % of measurements. Avalanche starting zones with a dominance of erosion are located on both the northern and southern slopes of the massif. Their exposure as well as the grain-size composition of soils are different. Such a pattern of slope morphodynamics in the summer season indicates that rainfall is the most important factor.

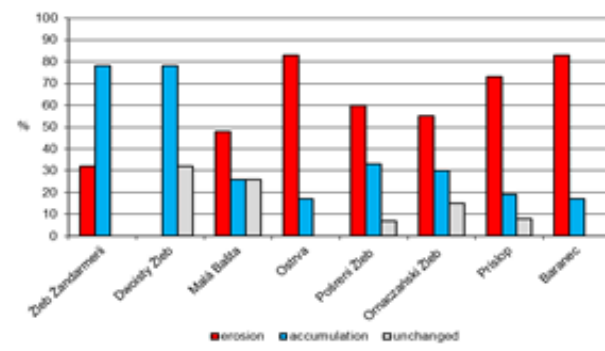


Figure 10 Morphodynamic changes at avalanches starting zones in the winter seasons in the years 2012–2016

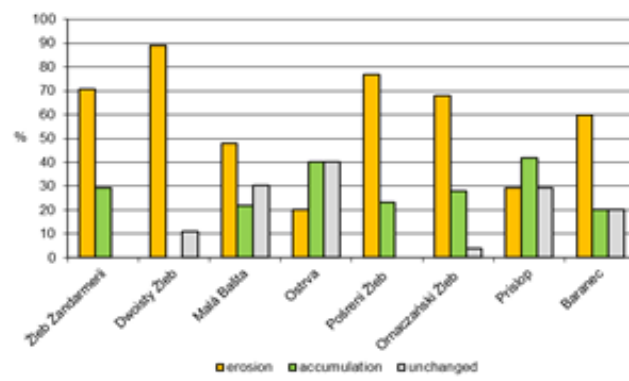


Figure 11 Morphodynamic changes at avalanches starting zones in the summer seasons in the years 2012–2015

4.5 Differentiation of slope morphodynamics in avalanche starting zones at a regional scale

The analysis of the results of measurements of slope morphodynamics in avalanche starting zones at the scale of the entire Tatra Mountains shows that erosion was found in 50% of all measurements, both in summer and winter seasons (Fig. 12). In addition, similar regularities are observed in accumulation, yet

accumulation was found in a smaller number of measurements (38% and 35%, respectively).

Differences occur when a separate analysis is made of the High Tatras and the Western Tatras (Fig. 13). In the summer season erosion dominates in both areas, occurring in more than 50% of the measurements. But in the winter season accumulation (55%) prevails in the High Tatras, while erosion (65%) prevails in the Western Tatras.

4.6 Differentiation of slope morphodynamics in subsequent years

Figure 14 presents the temporal variation of erosion and accumulation in the snow avalanche starting zones, in the form of yearly and seasonal changes. In general, the ratio between the different types of slope change (erosion, accumulation, unchanged) is more balanced in winter than in summer. Although a higher share of accumulation was found in winter, up to 40% of measurements, than in summer (only 25% of measurements), in the summer erosion occurs in up to 70% of measurements. In the winter its dominance was less pronounced, although the total share of erosion throughout the study period was higher than in summer.

5. Discussion

Research on the seasonal and spatial differentiation of snow avalanche starting zone morphodynamics is an attempt to answer the question of which processes are of greater importance in the development of erosional landforms – niches and scars within the starting zones. Are these cryogenic and nival processes, including avalanches and erosion, characteristic of the winter season or is erosion related to rainfall in the summer season? The results of the analysis of historical orthophotomaps indicate temporal and spatial variations in the development of erosional landforms within the avalanche starting zones in the Tatras associated with very different factors, but do not show regional or temporal regularities (Rączkowska et al., 2016b). At the same time, they clearly show a correlation between the enlarging of these forms and the

occurrence of large full-depth avalanches (Rączkowska et al., 2016b; Gądek et al. 2017).

The results of our research allow us to attempt an approximate assessment of the role of secular processes in the development of these erosional landforms in the Tatras. They indicate that slope changes are the effects of secular morphogenetic processes that are several times smaller than those previously observed as a result of snow avalanches (Stankoviansky and Midriak, 1998). However, they are similar to those obtained in previous studies of secular processes in the Tatras (Kotarba et al., 1987; Rączkowska, 2021). The average rates of lowering and accretion of slope surface, estimated from our measurements, are 8.4 mm/year and 4.2 mm/year respectively. These values are higher (by 1–2 mm/year) than those given by Midriak (1993) on the basis of research in the second half of the 20th century. It can be assumed that this is related to the influence of climate change on the course of secular morphogenetic processes. The results of our research, however, are an attempt to approximate the role of secular processes in the development of these erosional forms within the avalanche starting zones in the Tatras.

The pattern of slope changes in the avalanche starting zones caused by secular processes is complicated and ambiguous. It is difficult to define regularities in their spatial and temporal differentiation. Analysing them on a spatial scale, we found a dominance of erosion, both in the winter and summer seasons. It could therefore be assumed that the role of the activity of cryogenic processes and of meltwater erosion as well as of rainwater erosion in transforming the relief of the starting zones is similar. Moreover, a connection with the topography and features of slopes of the starting zones can be noted. The clear domination of erosion in the Western Tatras is favoured by the topography and elevation of avalanche starting zones. The slopes are not shaded there, as is often the case in the High Tatras, and the top layer of the soil thaws earlier. Moreover, slopes are mantled by weathering covers built with loose debris of different sizes including fine-grained mineral material.

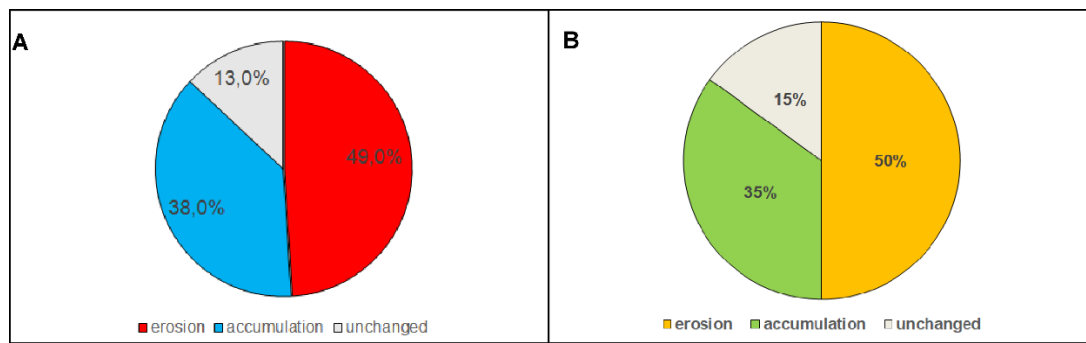


Figure 12 Diversity of morphodynamic changes in the avalanche starting zones between the winter (A) and the summer (B) seasons in the Tatras in 2012–2016

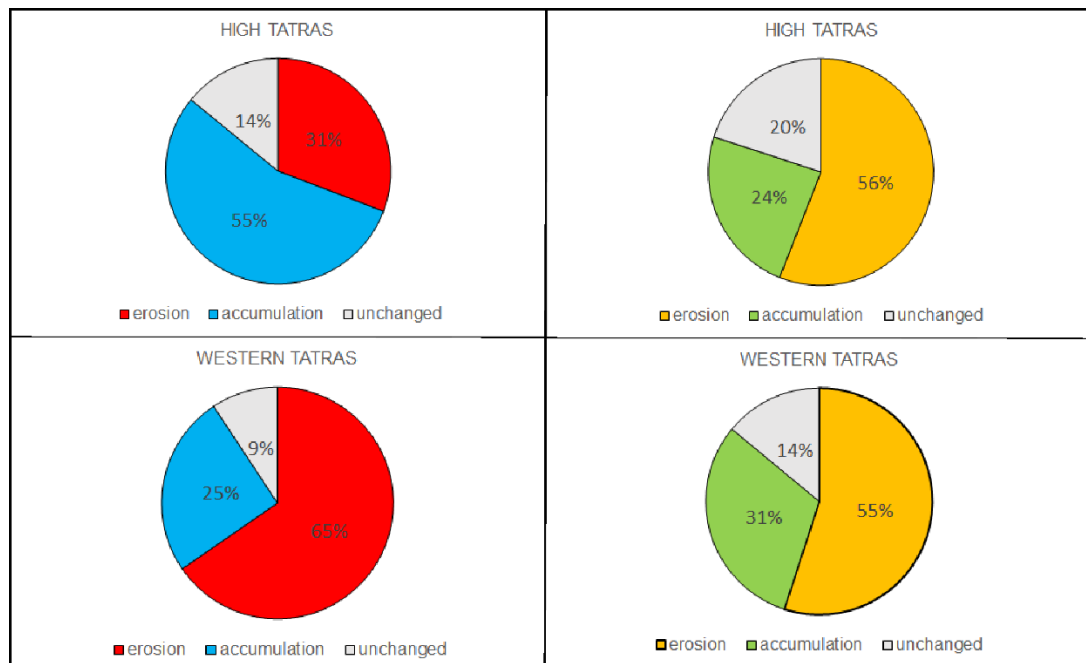


Figure 13 Regional diversity of morphodynamic changes in the avalanche starting zones between the winter (A, C) and summer (B, D) seasons in the Tatras in 2012–2016

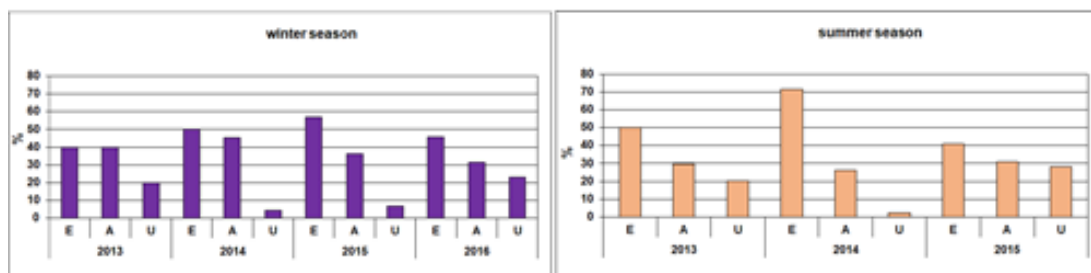


Figure 14 Temporal diversity of morphodynamics at the avalanche starting zones between particular winter and summer seasons. A – accumulation, E – erosion, U – no changes

When analysing the seasonal changes of slopes in the avalanche starting zones the relation to meteorological conditions can be noted. During summer the amount of erosion depends mainly on

rainfall. In the humid and cool summer of 2014, active erosion was occurring and there were few points where no change was found. In the 2013 and 2015 summer seasons with similar meteorological

conditions, the structure of morphodynamic change was also similar. Differences in the morphodynamics of the slopes during the winter are more difficult to relate to meteorological conditions. The duration and thickness of snow cover in 2013 and 2014 were similar and the ratio of erosion and accumulation differed. Rather, the occurrence of heavy precipitation in the period without snow cover is of importance. For example, the rainfall in May 2015 is likely to have resulted in a clear predominance of erosion over accumulation in the winter of 2014/2015 (Figs. 8 and 14). The nature of the precipitation is also important, e.g. in May 2014 there was heavy snowfall which was not reflected in the ratio of the amount of accumulation and erosion in the winter of 2013/2014.

6. Conclusions

The relief in the Tatra Mountains is conducive to the formation of avalanches. The analysis of slope inclination in the avalanche starting zones shows that in the High Tatras there are conditions for the formation of small powder snow avalanches of probable higher frequency, while in the Western Tatras, full-depth avalanches occur less frequently, but can be larger.

The morphogenetic role of avalanches depends on the occurrence of full-depth avalanches. In the period of the year when avalanches do not occur, slopes in their starting zones develop as a result of different morphogenetic secular processes related to rain or meltwater or cryogenic processes. Meltwater and rain water play a major role in slope modification. As a result, the material of the slope covers is triggered and moved in a chaotic and random manner, as well as being accumulated. The sites of erosion and accumulation of material are varied in time and space within the avalanche starting zones.

In general, erosion is the main effect of secular morphogenetic processes. This applies to both the winter and summer seasons. In the summer seasons, the intensity of modification of the slopes in the avalanche starting zones is related to the meteorological conditions, which is not the case in the winter seasons. The activity of secular morphogenetic processes maintains or develops the erosive scars or niches existing in avalanche starting zones. In this

way, it facilitates erosion caused by full-depth avalanches.

References

- Becht M. 1995. *Untersuchungen zur aktuellen Reliiefentwicklung in alpinen Einzugsgebieten*. Münchener Geographische Abhandlungen **47**: 1–187.
- Gądek B, Kaczka RJ, Rączkowska Z, Rojan E, Casteller A, Bebi P. 2017. Snow avalanche activity in Żleb Żandarmierii in a time of climate change (Tatra Mts., Poland). *Catena* **158**: 201–212.
<http://dx.doi.org/10.1016/j.catena.2017.07.005>
- Hess M. 1965. Piętra klimatyczne w polskich Karpatach Zachodnich. Zeszyty Naukowe UJ, *Prace Geograficzne* **11**: 1–267.
- Hreško J, Boltižar M, Bugár G. 2005. The present-day development of landforms and landcover in alpine environment – Tatra Mts (Slovakia). *Studia Geomorphologica Carpatho-Balcanica* **39**: 23–48.
- Jahn A. 1958. Mikrorelief peryglacialny Tatr i Babiej Góry. *Biuletyn Peryglacialny* **4**: 227–249.
- Jahn A. 1975. *Problems of the Periglacial Zone*. Państwowe Wydawnictwo Naukowe, Warszawa, 223 p.
- Klimaszewski M. 1988. *Rzeźba Tatr Polskich*. Państwowe Wydawnictwo Naukowe, Warszawa, 710 p.
- Kłapa M. 1980. Procesy morfogenetyczne i ich związek z sezonowymi zmianami pogody w otoczeniu Hali Gąsienicowej w Tatrach. *Dokumentacja Geograficzna Instytutu Geografii i Przestrzennego Zagospodarowania PAN* **4**: 1–55.
- Konček M., (ed.) 1974. *Klíma Tatier*. Veda, Bratislava, 855p.
- Kotarba A. 1976. Współczesne modelowanie węglanowych stoków wysokogórskich na przykładzie Czerwonych Wierchów w Tatrach Zachodnich. *Prace Geograficzne Instytutu Geografii i Przestrzennego Zagospodarowania PAN* **120**: 1–128.
- Kotarba A. 1992. High-energy geomorphic events in the Polish Tatra Mountains. *Geografiska Annaler* **74A**: 123–131. <https://doi.org/10.2307/521290>.
- Kotarba A. 1996. Sedimentation rates in the High Tatra lakes during the Holocene – geomorphic interpretation. *Studia Geomorphologica Carpatho-Balcanica* **30**: 51–61.
- Kotarba A., 2002. Współczesne przemiany przyrody nieożywionej. In: Borowiec W, Kotarba A, Krzan A (eds.) *Przemiany środowiska przyrodniczego Tatr. Tatrzański Park Narodowy–Polskie Towarzystwo Przyjaciół Nauk o Ziemi, Kraków–Zakopane*, 13–19.
- Kotarba A, Kaszowski L, Krzemien K. 1987. High-mountain denudational system in the Polish Tatra Mountains.

- Prace Geograficzne Instytutu Geografii i Przestrzennego Zagospodarowania PAN Spec. Issue **3**: 1–106.
- Lempa M, Kaczka RJ, Rączkowska Z. 2015. Morphological and morphometrical analyses reveal the avalanche influence over the talus cones in the Rybi Potok Valley, Tatra Mountains. *Studia Geomorphologica Carpatho-Balcanica* **49**: 15–33.
- Luckman BH. 1978. Geomorphic work of snow avalanches in the Canadian Rocky Mountains. *Arctic and Alpine Research* **10**: 261–276.
- McClung DM, Schaerer PA. 2006. *The Avalanche Handbook. Third edition*. The Mountaineers Books, Seattle, 288 p.
- Midriak R. 1993. *Únosnosť a racionálne využívanie územia vysokých pohorí Slovenska*. Publikáčne centrum ÚV ZSOPK, Bratislava, 114 p.
- Midriak R. 1996. Present-day processes and micro-landforms evaluation; case study of Kopske Sedlo, the Tatra Mts, Slovakia. *Studia Geomorphologica Carpatho-Balcanica* **30**: 35–50.
- Moore JR, Egloff J, Nagelisen J, Hunziker M, Aerne U, Christen M. 2013. Sediment Transport and Bedrock Erosion by Wet Snow Avalanches in the Guggigraben, Matter Valley, Switzerland. *Arctic, Antarctic, and Alpine Research* **45**: 350–362. DOI: 10.1657/1938-4246-45.3.350
- Niedźwiedź T, Łupikasza E, Pińskwar I, Kundzewicz ZW, Stoffel M, Małarzewski Ł. 2015. Variability of high rainfalls and related synoptic situations causing heavy floods at the northern foothills of the Tatra Mountains. *Theor Appl Climatol* **119**: 273–284. <https://doi.org/10.1007/s00704-014-1108-0>.
- Nemčok J, Bezák V, Biely A, Gorek A, Gross P, Halouzka R, Janák M, Kahan Š, Kotański Z, Lefeld J, Mello J, Reichwalder P, Rączkowski W, Roniewicz P, Ryka W, Wieczorek J, Zelman J. 1994. *Geological map of the Tatra Mountains*. Bratislava: MŽP SR, GÚDŠ, 26 p.
- Piotrowska K, Danel W, Iwanow A, Gaździcka E, Rączkowski W, Bezák V, Maglay J, Polák M, Kohút M, Gross P. 2015. *Geological map*. In: Atlas of the Tatra Mountains. Abiotic Nature, sheet IV.1, map 1 (1:100 000). Tatrzński Park Narodowy, Zakopane.
- Rapp A. 1960. Recent development of mountain slope in Kärkevagge and surroundings. *Geografiska Annaler* **17A**(2–3): 71–200.
- Rączkowska Z. 1999. Slope dynamics in the periglacial zone of the Tatra Mts. *Biuletyn Peryglacjalny* **38**: 127–133.
- Rączkowska Z. 2021. Współczesna ewolucja rzeźby Tatr. In: Kostrzewski A, Krzemień K, Migoń P, Starkel L, Winowski M, Zwoliński Z (eds.). *Współczesne przemiany rzeźby Polski*. Bogucki Wydawnictwo Naukowe, Poznań, 59–94. <https://doi.org/10.12657/9788379863822-03>
- Rączkowska Z, Długosz M, Rojan E. 2016. Geomorphological conditions of snow avalanches in the Tatra Mountains. *Zeitschrift für Geomorphologie* **60**(4): 285–297. DOI: 10.1127/zfg/2016/0289
- Rączkowska Z, Rojan E, Długosz M. 2016. The morphodynamics of slopes within the snow avalanche starting zones in the Tatras. *Geographia Polonica* **89**(1): 17–29.
- Rączkowski W, Boltziar M, Rączkowska Z. 2015. Relief. In: *Atlas of the Tatra Mountains*. Abiotic Nature, sheet V.1, map 1 (1:100 000). Tatrzński Park Narodowy, Zakopane.
- Sass O, Heel M, Hoinkis R, Wetzel KF. 2010. A six –year record of debris transport by avalanches on wildfire slope (Arnspitze, Tyrol). *Zeitschrift für Geomorphologie* **54**(2): 181–193.
- Stankoviansky M, Midriak R. 1998. The recent and present-day geomorphic processes in Slovak Carpathians. State of arts review. *Studia Geomorphologica Carpatho-Balcanica* **22**: 69–87.
- Ustrnul Z, Walawender E, Czekierda D, Šťastný P, Lapin M, Mikulová K. 2015. Precipitation and snow cover. In: *Atlas of the Tatra Mountains*, Abiotic Nature, sheet II.3, maps 1 and 5 (1: 250 000). Tatrzński Park Narodowy, Zakopane.
- Żmudzka E, Nejedlik P, Mikulova K. 2015. Temperature, thermal indices. In: *Atlas of the Tatra Mountains*, Abiotic Nature, sheet II. 2, map 1, (1: 250 000). Tatrzński Park Narodowy, Zakopane.

Bioturbation by grizzly bears in relict solifluction features of Glacier National Park, Montana, USA: A case study

Carol F. SAWYER^{1*}, Clayton J. WHITESIDES², Melanie B. STINE³

¹University of South Alabama, Department of Earth Sciences, Mobile, Alabama, 36688, United States of America

²Coastal Carolina University, Department of Anthropology and Geography, Conway, South Carolina, 29528, United States of America

³University of Texas-San Antonio, Department of Political Science and Geography, San Antonio, Texas, 78249, United States of America. Present affiliation: Independent scholar

Received 28 March 2022; Revised 19 December 2022; Accepted 19 December 2022

*Correspondence to: Carol F. SAWYER, e-mail: sawyer@southalabama.edu

ABSTRACT

Grizzly bears are an integral part of the northern Rocky Mountains ecosystem, where their foraging and denning leaves a measurable impact on the landscape. The purpose of this project was to evaluate the erosional effect of grizzly bears on relict solifluction tread and riser environments in the alpine tundra of Glacier National Park, Montana, USA. Grizzly bear excavation sites and material removed from vegetated risers and deposited downslope by bears was classified into either recent or decaying (i.e., not the current season) excavations, measured, and the volume of each excavation was calculated to determine the magnitude of disturbance by grizzly bears in this alpine environment. Grizzly bear activity was found at only one of four sample sites, where grizzlies removed 1.1727 m³ of material (new excavations = 0.6974 m³, old excavations = 0.4754 m³). The width of treads and risers was also measured to determine if there were differences in the dimensions of solifluction features where bear activity was observed. Although one of the study sites did have statistically wider treads and narrower risers than the other study sites, no grizzly bear activity was observed at that site, suggesting that excavations are related to factors intrinsic to solifluction features. A conceptual model of the degradation of turf was developed based on observations of vegetation and soil removed by bears, illustrating how foraging activity in a tread and riser environment may produce micro-scale changes in the landscape over time.

KEYWORDS Zoogeomorphology; Grizzly bears; Bioturbation; Relict solifluction; Glacier National Park

1. Introduction

In subalpine and treeline regions, grizzly bears (*Ursus arctos horribilis*) forage by digging for plant roots and bulbs (Butler, 1992; Mattson, 1997; Tardiff and Stanford, 1998), cutworm moths (White et al., 1998), and small mammals (Doak and Loso, 2003). These foraging activities have resulted in grizzly bears being cited as substantial erosional agents in these environments (Butler, 1992).

Grizzlies have been documented in alpine areas above treeline, but their geomorphic effects have often been cursory and the existing literature is contradictory. Hamer and Herrero (1987) stated that the alpine environment was unimportant as a food source for grizzly bears, despite numerous sightings of grizzlies above 1829 m during summer months in Glacier National Park, Montana, USA (GNP; Martinka, 1972). Butler (1992) noted that grizzly bears in GNP foraged in the alpine zone, and in the Canadian Rockies it has been suggested that “during the summer months, the bears spend most of their time digging for food above the treeline” (Hall et al., 1999, p. 437).

Although grizzly bears dig deep into the soil when in pursuit of ground squirrels, digging for plant-based food, including roots, results in removal of only the top layer of sod (Doak and Loso, 2003). In some alpine and subpolar environments, sod may be limited to turf-banked terraces, described as linear step-like features with unsorted stone treads and vegetated turf risers (Benedict, 1970; Butler et al., 2004). These relict solifluction features protect underlying fine-grained sediments (Walsh et al., 2003). When the turf bank is disturbed, however, by bears, ungulates, or frost heaving (Benedict, 1970; Pérez, 1993; Grab, 2002), the terraces may become susceptible to other erosional processes (Walsh et al., 2003).

The environment wherein both turf-banked terraces and grizzly bears occur in GNP provides an ideal venue to assess the potential for grizzlies to modify relict solifluction features, which are likely relatively stable features that resist erosion, despite active surface movement (Sawyer, 2007).

From a zoogeomorphic perspective, grizzly bears have the ability to modify directly the alpine tundra by trampling, digging for food, and con-

structing dens (Butler, 1995). In a subalpine environment, Butler (1992) calculated 0.3 m³ of material had been removed by a grizzly bear digging for food; furthermore, he estimated that a single grizzly bear may be responsible for 6.8 m³ yr⁻¹ of erosion in GNP from denning, digging, and foraging. White et al.'s (1998) analysis of grizzly bear feeding in the alpine of GNP focused on grizzly bear consumption of cutworm moths in talus slopes, not turf-banked terraces. Although the focus of their research was not zoogeomorphology per se, White et al. (1998) concluded that approximately 0.22 m³ of talus debris was excavated from 30 oval pits dug by grizzly bears. Tardiff and Stanford (1998) evaluated the effect of grizzly bear digging on nitrogen availability in subalpine meadows of GNP and estimated that a single foraging event covered an area of >15 m² and was characterized by overturned chunks of soil and plant roots to a depth of approximately 10 cm. In the Rocky Mountains of Canada, Hall et al. (1999) identified the erosional impact of grizzly bears above treeline to be as much as 0.4958 m³ per m⁻².

Scant knowledge exists of the change, modification, or recovery of turf-banked terraces following surficial disturbances by large mammals. In alpine areas, needle ice (small filaments of ice that form in freezing temperatures) has been attributed to turf exfoliation, or the process of destroying “a continuous ground vegetation cover by removing the soil exposed along small terrace fronts” (Pérez, 1992, p. 82).

Needle ice can disturb soil and prevent vegetation growth (French, 1996). Previous research (Pérez, 1992, 1993; Grab, 2002; Butler et al., 2004), however, has suggested that for needle ice to cause turf exfoliation, another process is first needed to disrupt the thick turf and expose the underlying soil. Pérez (1993), Grab (2002), and Butler et al. (2004) suggested that animals could interrupt turf cover by trampling or pawing at the ground.

Any behaviour by animals, including burrowing and digging for food, also has the ability to disturb turf. A possible consequence of grizzly bear digging along turf-banked terraces is terrace retreat through erosion of risers.

2. Methods

2.1 Study Area

GNP (Figure 1) contains a stable grizzly bear population and relict solifluction-related turf-banked terraces containing treads and risers (Hayward, 1989; Butler et al., 2004). The vegetation within these alpine turf-banked terraces is mostly *Dryas octopetala* (Bamberg and Major, 1968), which, where present, provides a nearly continuous protective vegetated cover.

Four study sites were selected (Table 1), using aerial imagery, personal observation, and published literature (Bamberg and Major, 1968; Butler and Malanson, 1989; Tardiff and Stanford, 1998; White et al., 1998; Butler and Malanson, 1999; Resler et al.,

2005; Butler et al., 2009; Butler, 2011). The primary criterion for inclusion was the presence of well-developed, vegetated solifluction treads and risers; the sites were not chosen because of known grizzly bear presence.

All study sites were located on or east of the Continental Divide, ensuring similar precipitation and temperature patterns. Diurnal freezing is possible during all months of the year, with mean monthly temperatures below freezing for 6 months (November to April). Precipitation averages 677 mm per year, with the driest month (August) recording 43 mm and the wettest month (June) receiving 90 mm. Snowfall is possible all months of the year (WRCC, n.d.).

Legend

- ▲ Study Sites
- Glacier NP
- Continental Divide
- Towns
- Local Roads

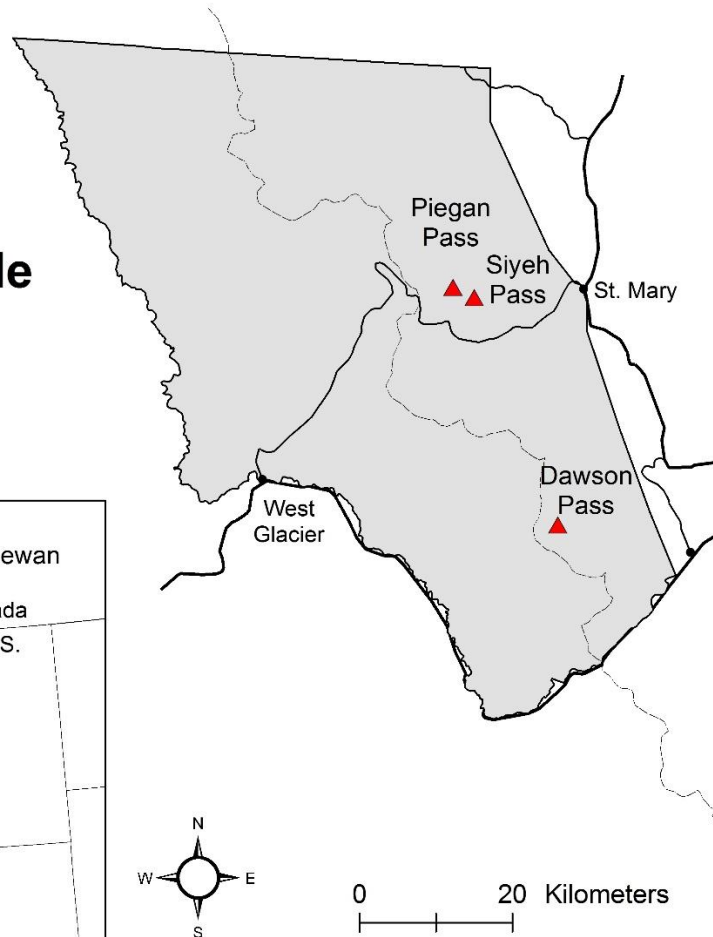


Figure 1 Study area map illustrating the location of study sites in Glacier National Park, Montana, USA. The sites were located above treeline, on or east of the Continental Divide

Table 1 Characteristics of study sites

Site	Surficial deposit	Elevation (m)	Aspect
Siyeh Pass 1 (SP 1)	Solifluction frost rubble	2362	SE
Siyeh Pass 2 (SP 2)		2389	E–NE
Dawson Pass (DP)		2286	E
Piegan Pass (PP)		1900	N–NW

2.2 Data Collection and Analysis

We identified inactive solifluction treads and risers above alpine treeline at Siyeh Pass that contained grizzly bear diggings as well as two other sites, Dawson Pass and Piegan Pass, where no bear activity was observed, despite similar site conditions

among all locations (Figure 2). Field visits and data collection occurred during the summers of 2010 and 2011 and two separate field visits occurred in 2011 (mid-July and mid-September) to document seasonal excavation by bears. No new excavations, however, were observed in September 2011.

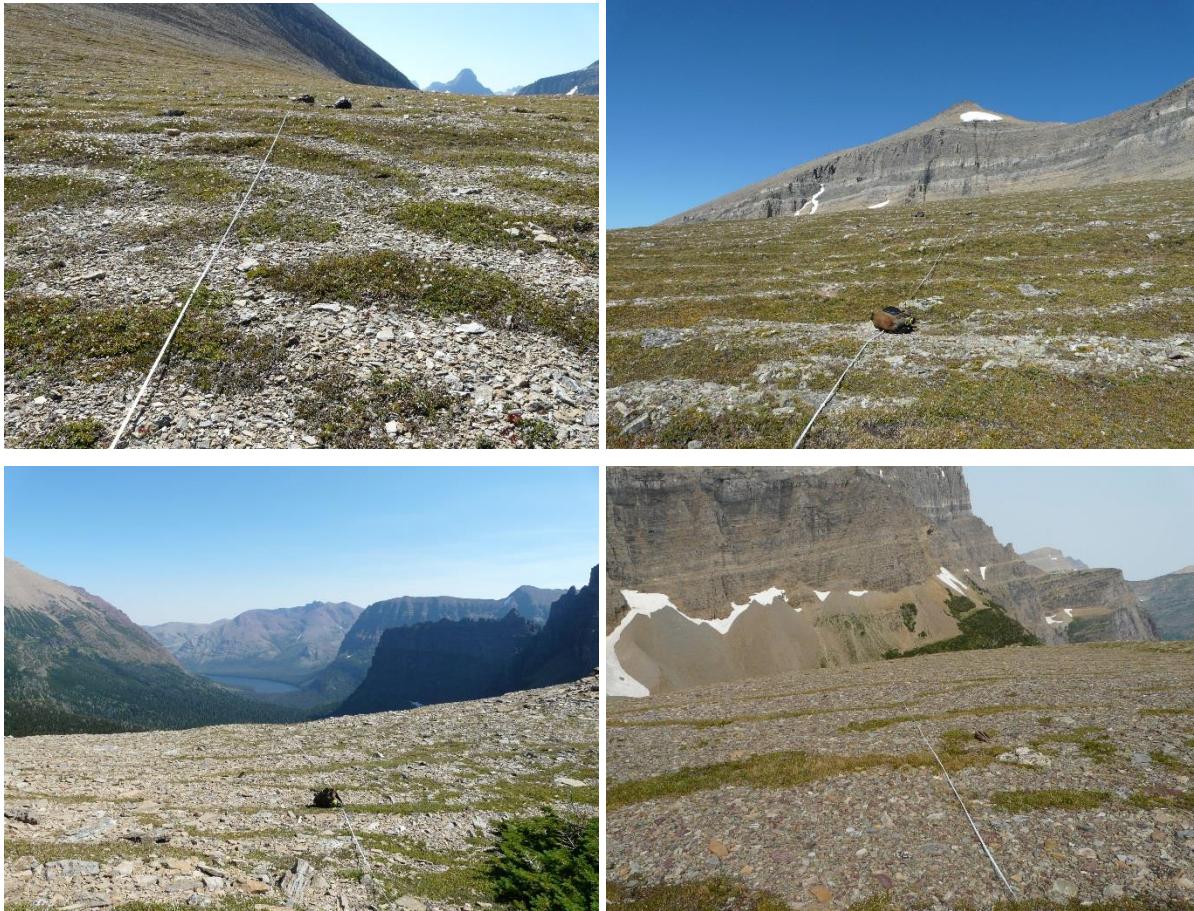


Figure 2 Photos of study sites: clockwise from upper left: Siyeh Pass 1; Siyeh Pass 2; Piegan Pass; Dawson Pass. Each site was located on a ridge above a cirque



Figure 3 Photo of bear excavations (arrows) from vegetated solifluction risers with spoils deposited on downslope treads at Siyeh Pass

At Siyeh Pass, chunks or wedges of vegetation and soil resting on adjacent, downslope tread surfaces characterized recent grizzly bear excavations (Figure 3). Grizzly bears were considered responsible because our observations paralleled those of Hall et al. (1999) who noted, “it was possible to discern the digging effect in four instances of a single paw” (p. 437). Moreover, other mammals that reside near or frequent the alpine tundra (e.g., marmots (*Marmota* sp.), bighorn sheep (*Ovis canadensis*), and mountain goats (*Oreamnos americanus*) create different patterns of disturbance and are not known to dislodge turf from risers. Differentiation between fresh (i.e., dug that summer) and older digs was evident by sediment infilling, vegetation establishment within older depressions (Guterman et al., 1990; Doak and Loso, 2003), and degradation of the shape of the excavated material. Determining the age of depressions older than one year was not possible because

of varying rates of excavated sod decay and infilling of depressions (Tardiff and Stanford, 1998). Excavation depths for 30 recent (dug that summer) and 30 decaying (older than one year) depressions were recorded in the center of excavated holes found within two 30 x 30 m quadrats that were randomly placed on the landscape. The long and short axes of each excavation were measured, resulting in length, width, and depth data for each grizzly bear disturbance. Measurements of freshly excavated material and older spoils were taken during the same site visit to eliminate any size differences between visits. Although we cannot guarantee that all content removed from the hole was still present in downslope spoil mounds, the reinsertion of excavated material into their original holes suggested that most material was present and had not yet eroded. Volume was calculated by the cuboid formula (Butler, 1992),

using the long and short axes of the excavated material and the depth of the hole in the riser.

In an effort to determine if micro-site characteristics explained why grizzly bear activity was present at Siyeh Pass and not at Dawson Pass and Piegan Pass, the widths of the solifluction treads and risers were recorded at the four study sites by placing three 30–50 m transects perpendicular to the con-

tours of the slope. The height of each riser was recorded with a measuring tape placed perpendicular to the tread below the riser, measured to the top of the riser. Transect lengths were 50 m, unless the tread and riser topography did not extend for a full 50 m, in which case, 30 m transects were used. Inferential and descriptive statistics were used to analyse the data.

Table 2 Mean, standard deviation, and median of old and new diggings

	Mean ± Standard deviation (median)			
	Length (cm)	Width (cm)	Depth (cm)	Total Volume (m ³)
Old diggings (n=30)	49.73±20.97 (42.5)	36.47 ±14.98 (33)	7.85±1.76 (7.75)	0.4754
New diggings (n=30)	49.30±19.86 (41.5)	34.20±9.55 (33)	12.55±3.69 (11.5)	0.6974

3. Results and Discussion

Recent excavations (i.e., dug that season; $M = 12.55$, $SD = 3.69$) were significantly deeper than decaying (old) excavations ($M = 7.85$, $SD = 1.76$; $t(29) = 7.086$, $p \leq 0.001$). Despite differences in age and the appearance that fresh excavations better retained their shape, the lengths of new ($M = 49.30$, $SD = 19.86$) and old ($M = 49.73$, $SD = 20.97$) excavations were surprisingly similar and non-significant ($t(29) = -0.080$, $p = 0.937$), which was also the case for widths of new ($M = 34.20$; $SD = 9.55$) and old ($M = 36.47$; $SD = 14.98$) excavations ($t(29) = -0.668$, $p = 0.509$; Table 2). The total volume of soil removed from the 60 samples was 1.1727 m^3 (recent = 0.6974 m^3 , decaying = 0.4754 m^3). A one-way ANOVA revealed a statistical difference between riser widths at the study sites ($F(3, 385) = 4.6001$, $p = 0.004$), and a Tukey's HSD post-hoc test indicated that the statistical difference existed between Siyeh Pass and Dawson Pass ($p = 0.017$, 95% C.I. = -41.15 , -2.85) and between Piegan Pass and Dawson Pass ($p = 0.008$, 95% C.I. = -44.07 , -4.73). Similar significant differences were found for tread widths ($F(3, 368) = 14.137$, $p \leq 0.000$), where Piegan Pass had significantly wider treads than either site at Siyeh Pass ($p \leq 0.000$, 95% C.I. 20.82 , 65.18 ; $p \leq 0.000$, 95% C.I.

15.44 , 64.56) or Dawson Pass ($p \leq 0.000$, 95% C.I. = 32.77 , 83.23 ; Table 3). In addition, a one-way ANOVA showed that riser heights were also found to be significantly different ($F(3, 358) = 53.9$, $p \leq 0.000$) between study sites. A Tukey's HSD post-hoc test indicated that significant statistical differences existed with the riser heights between all study sites with six relationships tested: SP1:SP2 ($Q = 9.20$, $p \leq 0.000$); SP1:DP ($Q = 8.93$, $p \leq 0.000$); SP1:PP ($Q = 5.46$, $p \leq 0.001$); SP2:DP ($Q = 18.13$, $p \leq 0.000$); SP2:PP ($Q = 3.74$, $p = 0.043$); DP:PP ($Q = 14.39$, $p \leq 0.000$).

The depth of bear excavations in risers appeared to be greatest in the initial year, with infilling over time due to secondary erosional processes (e.g., fluvial, aeolian, etc.). The length and width of both new and old excavations were not statistically different. Butler (1992) estimated 0.3 m^3 of material was excavated while digging for food at a subalpine site whereas our data indicated that almost 0.7 m^3 had been excavated at an alpine site, which is logical as vegetation provides a non-continuous cover in the alpine region, requiring bears to excavate more area for food. Alpine vegetation may be worth the extra energy expenditure, however, as plants at higher elevations in the Rocky Mountains have been shown to have higher caloric content than plants at

lower elevations in the Appalachian Mountains (Andersen and Armitage, 1976). This trend is consistent with increased nutrient concentration at

higher elevations at several global sites (Körner, 1989).

Table 3 Mean and standard deviation of riser heights and widths, as well as tread widths.
All measurements are in centimetres

Site	Mean $\pm$ Standard deviation (n)		
	Riser heights	Riser widths	Tread widths
Siyeh Pass 1 (SP 1)	26.1 $\pm$ 10.7	99.2 $\pm$ 48.5	118 $\pm$ 58.1
	(n=113)	(n=113)	(n=117)
Siyeh Pass 2 (SP 2)	13.4 $\pm$ 5.4	111 $\pm$ 55.1	121 $\pm$ 82.6
	(n=78)	(n=78)	(n=79)
Dawson Pass (DP)	38.56 $\pm$ 24.5	113.4 $\pm$ 61.4	103 $\pm$ 51.8
	(n=71)	(n=71)	(n=72)
Piegan Pass (PP)	18.6 $\pm$ 5.7	89 $\pm$ 32.2	161 $\pm$ 61.0
	(n=100)	(n=100)	(n=104)

It has been suggested that locations where bears dig for ground squirrels were determined more by a bear's presence in the alpine than by specific micro-site characteristics (Doak and Loso, 2003). Grizzlies may use alpine environments as travel corridors and take advantage of convenient food sources while in transit. Insects are readily transported by aeolian processes and deposited in alpine environments. High mountain snowbanks serve as catchment areas for these insects, which remain stranded on the snow (Van Dyke, 1919) and have been cited as a food source for bears (Gurney, 1953 and references therein). Insects deposited on exposed rock and tundra vegetation have also been documented in large quantities in the White Mountains of California (Spalding, 1979) and insect activity in western Montana during summer months has been shown to increase with elevation (Chapman, 1954), where grizzlies have been observed feeding on ladybird beetle and army cutworm populations at elevations above 3000 m (Chapman et al., 1955). Although Piegan Pass did have statistically wider tread and nar-

rower riser widths than most of the other study sites, our measurements were comparable with other solifluction features in eastern GNP (Butler et al., 2004). Additionally, grizzly bear activity was not observed at Piegan Pass, suggesting that regardless of the reason for grizzly bear presence in the alpine (e.g., transit, food), their excavations appear to be related to factors intrinsic to solifluction features, whether significant or not, not solely the presence of the bears, which is contrary to the findings reported by Doak and Loso (2003).

Our findings suggest that grizzly bears have potential to modify the microscale geomorphology of alpine tundra through excavation. As noted above, debris was located downslope from the excavated site with no excavated debris found upslope from the excavation. A conceptual model of possible microscale response to a single excavation (Figure 4) illustrates how the removal of turf from a riser, through grizzly bear excavation, facilitates erosion, contributing to the overall decay of relict solifluction treads and risers. For the reason that alpine tundra

vegetation is slow to re-establish following disturbance (Bell and Bliss, 1973; Ebersole, 2002), fine-scale slope retreat may occur as the riser erodes. It has been argued that the geomorphological features of dynamic upland environments in Scotland were

"crucial in maintaining habitat diversity and dynamic equilibrium" (Gordon, et al. 2001, p. 327), and this habitat diversity is apparent in conifer seedling establishment within solifluction features in GNP (Butler et al., 2004; Resler et al., 2005; Resler, 2006).

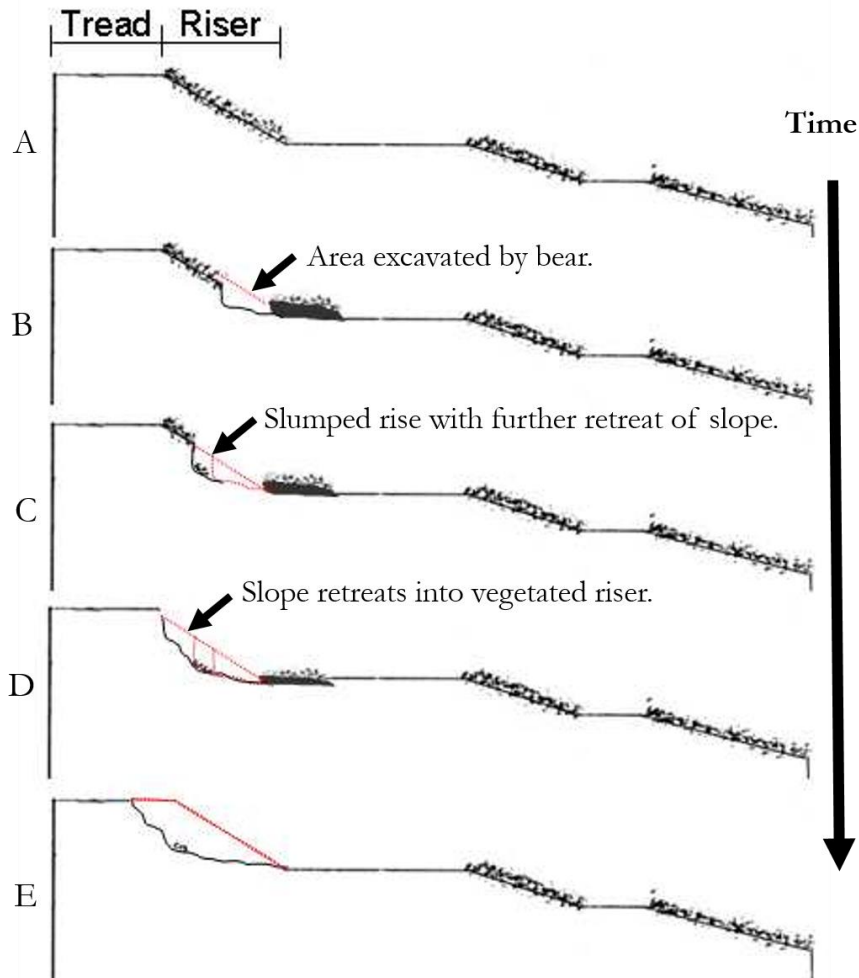


Figure 4 Conceptual model illustrating how a riser may be modified following excavation by a bear

Additionally, disruptions in solifluction turf-banked terraces may provide sites for conifer establishment above current treeline (Walsh et al., 2003), and fine-scale disturbances, especially those adjacent to treeline, have significantly higher rates of conifer germination (Whitesides and Butler, 2016; Kambo and Danby, 2018). Despite mentions of animal activity within the tread and riser environment (*sensu* Butler, 1995; Walsh et al., 2003), scant research exists on the factors that degrade relict solifluction features and how degradation may affect vegetation dynamics and the longevity of these landforms, particularly in an era of changing climate.

4. Conclusions

This case study suggests that grizzly bear activity above alpine treeline is occurring within specific landforms and grizzlies should be considered erosional agents contributing to the degradation of relict solifluction features. These findings also contribute to and corroborate the limited existing literature on grizzlies as geomorphic agents above treeline. Alpine tundra may become increasingly important to bears as the effects of climate change alter vegetation throughout GNP (Hall and Fagre, 2003) and other mountainous regions. Continued

study of bear activity on fine-scale solifluction features is necessary to reveal and monitor the extent of these geomorphic agents on the fragile alpine environment.

Acknowledgements

This work was supported by a University of South Alabama Faculty Research Development Council Award (Sawyer).

References

- Andersen DC, Armitage KB. 1976. Caloric content of Rocky Mountain subalpine and alpine plants. *Journal of Range Management* **29**(4): 344–345. DOI: 10.2307/3897103.
- Ballantyne CK. 2008. After the ice: Holocene geomorphic activity in the Scottish Highlands. *Scottish Geographical Journal* **124**(1): 8–52. DOI: 10.1080/14702540802300167.
- Bamberg SA, Major J. 1968. Ecology of the vegetation and soils associated with calcareous parent materials in three alpine regions of Montana. *Ecological Monographs* **38**(2): 127–167. <https://www.jstor.org/stable/1942290>
- Bell KL, Bliss LC. Alpine disturbance studies: Olympic National Park, USA. *Biological Conservation* **5**(1): 25–32.
- Benedict JB. 1970. Downslope movement in a Colorado alpine region: Rates, processes, and climatic significance. *Arctic and Alpine Research* **2**(3): 165–226. DOI: 10.1080/00040851.1970.12003576.
- Butler DR. 1992. The grizzly bear as an erosional agent in mountainous terrain. *Zeitschrift für Geomorphologie* **36**(2): 179–189. DOI: 10.1127/zfg/36/1992/179.
- Butler DR. 1995. *Zoogeomorphology: Animals as geomorphic agents*. Cambridge University Press, New York. 231 p.
- Butler DR, Malanson GP. 1989. Periglacial patterned ground, Waterton-Glacier International Peace Park, Canada and U.S.A. *Zeitschrift für Geomorphologie* **33**(1): 43–57. DOI: 10.1127/zfg/33/1989/43.
- Butler DR, Malanson GP. 1999. Site locations and characteristics of miniature patterned ground, eastern Glacier National Park, Montana, U.S.A. *Landform Analysis* **2**: 45–49.
- Butler DR, Malanson GP, Resler LM. 2004. Turf-banked terrace treads and risers, turf exfoliation and possible relationships with advancing treeline. *Catena* **58**(3): 259–274. <https://doi.org/10.1016/j.catena.2004.05.003>
- Butler DR, Malanson GP, Resler LM, Walsh SJ, Wilkerson FD, Schmid GL, Sawyer CF. 2009. Geomorphic Patterns and processes at alpine treeline. In: Butler DR, Malanson GP, Walsh SJ, Fagre DB (eds.), *The Changing Alpine Treeline: The Example of Glacier National Park, MT, USA*. Elsevier, The Netherlands, 63–84.
- Carrara PE. 1990. *Surficial Geologic Map of Glacier National Park, Montana*. USGS Map 1-1508-D, Miscellaneous Investigations Series. <https://doi.org/10.3133/i1508D>
- Chapman JA. 1954. Studies on summit-frequenting insects in Western Montana. *Ecology* **35**(1): 41–49. <https://doi.org/10.2307/1931402>
- Chapman JA, Romer JI, Stark J. 1955. Ladybird beetles and army cutworm adults as food for grizzly bears in Montana. *Ecology* **36**(1): 156–158. <https://doi.org/10.2307/1931444>
- Doak D, Loso MG. 2003. Effects of grizzly bear digging on alpine plant community structures. *Arctic, Antarctic, and Alpine Research* **35**(4): 421–428. DOI: 10.1657/1523-0430(2003)035[0421:EOGBDO]2.0.CO;2
- Ebersole JJ. 2002. Recovery of alpine vegetation on small, denuded plots, Niwot Ridge, Colorado, U.S.A. *Arctic, Antarctic, and Alpine Research* **34**(4): 389–397. <https://doi.org/10.2307/1552196>
- Gordon JE, Brazier V, Thompson DBA, Horsfield D. 2001. Geo-ecology and the conservation management of sensitive upland landscapes in Scotland. *Catena* **42**(2–4): 323–332. <https://www.jstor.org/stable/3566137>
- Grab SW. 2002. Turf exfoliation in the high Drakensberg, southern Africa. *Geografiska Annaler* **84A**(1): 39–50. DOI: 10.1111/j.0435-3676.2002.00160.x
- Gutterman Y, Golan T, Garsani M. 1990. Porcupine diggings as a unique ecological system in a desert environment. *Oecologia* **85**(1): 122–127. DOI: 10.1007/BF00317352
- Hall K, Boelhouwers J, Driscoll K. 1999. Animals as erosional agents in the alpine zone: Some data and observations from Canada, Lesotho, and Tibet. *Arctic, Antarctic, and Alpine Research* **31**(4): 436–446. DOI: 10.1080/15230430.1999.12003328
- Hall MHP, Fagre DB. 2003. Modeled climate-induced glacier change in Glacier National Park, 1850–2100. *BioScience* **53**(2): 131–140. [https://doi.org/10.1641/0006-3568\(2003\)053\[0131:MCIGCI\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2003)053[0131:MCIGCI]2.0.CO;2)
- Hamer D, Herrero S. 1987. Grizzly bear food and habitat in the Front Ranges of Banff National Park, Alberta.

- Bears: Their Biology and Management* **7**: 199–213. <https://www.jstor.org/stable/3872626>
- Hayward GD. 1989. Historical grizzly bear trends in Glacier National Park, Montana: A critique. *Wildlife Society Bulletin* **17**(2): 195–197. <https://www.jstor.org/stable/3782651>
- Kambo D, Danby RK. 2018. Influences of fine-scale disturbance on germinant success in a treeline ecotone. *Physical Geography* **39**(5): 471–486. DOI: 10.1080/02723646.2018.1434926
- Körner C. 1989. The Nutritional Status of Plants from High Altitudes. A Worldwide Comparison. *Oecologia* **81**(3): 379–391. <https://doi.org/10.1007/BF00377088>
- Martinka CJ. 1972. *Habitat relationships of grizzly bears in Glacier National Park, Montana*. National Park Service Progress Report. West Glacier, Montana. 19 pp.
- Mattson DJ. 1997. Selection of microsites by grizzly bears to excavate biscuitroots. *Journal of Mammalogy* **78**(1): 228–238. <https://doi.org/10.2307/1382656>
- Pérez FL. 1992. Processes of turf exfoliation (Rasenabschälung) in the high Venezuelan Andes. *Zeitschrift für Geomorphologie* **36**(1): 81–106.
- Pérez FL. 1993. Turf destruction by cattle in the high equatorial Andes. *Mountain Research and Development* **13**(1): 107–110. <https://www.jstor.org/stable/3673648>
- Resler LM. 2006. Geomorphic controls of spatial pattern and process at alpine treeline. *The Professional Geographer* **58**(2): 124–138. DOI: 10.1111/j.1467-9272.2006.00520.x
- Resler LM, Butler DR, Malanson GP. 2005. Topographic shelter and conifer establishment and mortality in an alpine environment, Glacier National Park, Montana. *Physical Geography* **26**(2): 112–125. DOI: 10.2747/0272-3646.26.2.112
- Sawyer CF. 2007. *Frost heaving and surface clast movement in turf-banked terraces, eastern Glacier National Park, Montana*. Texas State University-San Marcos. PhD thesis.
- Selkirk JM. 1998. Active vegetation-banked terraces on Macquarie Island. *Zeitschrift für Geomorphologie* **42**(4): 483–496.
- Smith DJ. 1992. Long-term rates of contemporary solifluction in the Canadian Rocky Mountains. In: Dixon JC, Abrahams AD (eds.), *Periglacial Geomorphology*. Wiley, Chichester, 203–221.
- Spalding JB. 1979. The Aeolian ecology of White Mountain Peak, California: Windblown insect fauna. *Arctic and Alpine Research* **11**(1): 83–94. <https://doi.org/10.2307/1550461>
- Tardiff SE, Stanford JA. 1998. Grizzly bear digging: Effects of subalpine meadow plants in relation to mineral nitrogen availability. *Ecology* **79**(7): 2219–2228. DOI: 10.1890/0012-9658(1998)079[2219:GBDEOS]2.0.CO;2
- Van Dyke EC. 1919. A few observations on the tendency of insects to collect on ridges and mountain snowfields. *Entomological News* **30**(9): 241–244.
- Walsh SJ, Butler DR, Malanson GP, Crews-Meyer KA, Messina JP, Xiao N. 2003. Mapping, modeling, and visualization of the influences of geomorphic processes on the alpine treeline ecotone, Glacier National Park, MT, USA. *Geomorphology* **53**(1–2): 129–145. DOI: 10.1016/S0169-555X(02)00350-1
- White Jr. D, Kendall KC, Picton HD. 1998. Grizzly bear feeding activity at alpine army cutworm moth aggregation sites in northwest Montana. *Canadian Journal of Zoology* **76**(2): 221–227. DOI: 10.1139/z97-185
- Whitesides CJ, Butler DR. 2016. Bioturbation by gophers and marmots and its effects on conifer germination. *Earth Surface Processes and Landforms* **41**(15): 2269–2281. DOI:10.1002/esp.4046
- Western Regional Climate Center (WRCC). n.d. Daily Temperature and precipitation for St. Mary, Montana (247292) Cooperative Station <http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?mt7292>. Accessed 8 September 2021.

Miscellanea

Symposium

37th Romanian National Symposium on Geomorphology

Sinaia, June 15-19, 2022

The Romanian National Symposium on Geomorphology (RNSG) is the annual event of Romanian geomorphologists. In 2022, the 37th edition took place in 15-19th of June in the city of Sinaia and it was organized by Romanian Association of Geomorphologists and Faculty of Geography, University of Bucharest, with the title of "*Geomorphology under modern challenges: Uncertainties and Perspectives*".

The symposium began with the Young Geomorphologists Day (YGD) which gathered bachelor, master and phd students from University of Bucharest, University of Suceava and University of Craiova. Two practical activities were organized outdoors on the eastern slopes of Bucegi Mountains: one fo-

cused on preparing and carrying out an aerial survey using UAS with ground control points and another introductory course in dendrochronology focused on how to extract cores from deciduous trees using an increment borer. The first course was led by Lecturer Florin Tătui and Răzvan Popescu (Faculty of Geography, University of Bucharest) while the second course was organized by Prof. Mircea Voiculescu (Department of Geography, West University of Timișoara). The YGD also benefitted from the support and participation of Professor Jasper Knight (University of the Witwatersrand, Johannesburg, South Africa) and Professor Sandu Boengiu (Department of Geography, University of Craiova).



The scientific communications comprised two key note lectures, 19 oral presentations and 11 poster presentations. They were organized in several scientific sessions: Mountain geomorphology and slope processes, Paleo-environmental reconstructions, Geomorphometry and fluvial geomorphology, Coastal geomorphology and Applied geomorphology.

Most of the communications were presented on site but online participation was also allowed. In total, more than 40 people participated from Bucharest, Timișoara, Suceava, Iași, Cluj-Napoca, Craiova and Constanța. The Symposium benefitted from two

invited key note presentations: "Permafrost and large slope instabilities – observations, models and implications" by Prof. Dr. Bernd Etzelmüller from University of Oslo, Norway and "The geomorphological sensitivity of mountain systems" by Prof. Dr. Jasper Knight from University of the Witwatersrand, Johannesburg, South Africa.

Two practical applications were organized during the RNSG both in the Bucegi Mountains. The first field trip was organized in Sinaia Ski Area on June 16 with the main theme of snow avalanche hazards and risks.



Scientific discussions were led by Prof. Dr. Mircea Voiculescu and Lect. Dr. Alexandru Onaca from West University of Timișoara which discussed about the control of topographic and anthropogenic parameters on avalanche release and methods of assessing spatial and temporal avalanche activity including mainly dendrochronology approach. The second

fieldtrip was organized on the Bucegi Plateau on June 18 with the subject of frost weathering and solifluction (discussions led by Dr. Mirela Vasile and Prof. Dr. Petru Urdea) and also the deglaciation chronology in the light of newly obtained absolute ages (discussions led by Lect. Dr. Răzvan Popescu, University of Bucharest).



Răzvan Popescu, *University of Bucharest*

International conference

International Conference on Geomorphology, 10th Edition, Coimbra, Portugal, 12-16 September 2022

The 10th International Conference on Geomorphology (ICG) was organized by International Association of Geomorphologists (IAG) and Portuguese Association of Geomorphologists (APGeom) and co-organized by the Centre of Studies in Geography and Spatial Planning (CEGOT), the Department of Geography and Tourism (University of Coimbra), and the Department of Earth Sciences (University of Coimbra) at Convent of St. Francis on the left bank of Mondego River from the 12th to the 16th of September, 2022. The title of the conference was "Geomorphology and Global Change", it included 24 scientific sessions (General and Historic Geomorphology, Methods and Techniques in Geomorphology, Geomorphological Mapping, GIS, Remote Sensing and Modelling, Forms, Processes and Landscape Change, Climatic Geomorphology, Mountain Geomorphology, Glacial and Periglacial Geomorphology, Tectonic and Seismic Geomorphology, Fluvial Geomorphology, Aeolian Geomorphology, Marine and coastal geomorphology, Volcanic Geomorphology, Karst Geomorphology, Weathering,

Soils and Landforms, Biogeomorphology and Wetlands, Applied Geomorphology, Hillslope Processes and Landforms, Geomorphological Hazards and Risk Management, Wildfires and Soil Erosion, Sustainability in Geomorphology: Anthropocene and Urban Geomorphology, Geoarchaeology, Connectivity in Geomorphology, Geoheritage, Cultural Geomorphology and Geotourism and Planetary Geomorphology) and 2 plenary lectures (Monique Fort from Université de Paris Diderot with "Geomorphology: a key discipline documenting climate change at different spatio-temporal scales" and José Luís Zêzere from Universidade de Lisboa, with "Geohazards in Portugal: a state of the art"). At the time of the Conference 7 field trips were scheduled and available (1 pre-Conference, 3 on Wednesday during the Conference week and 3 post-Conference) and an intensive course for young researchers that was dedicated to the following topic "Geomorphological changes in landscapes affected by fire: field and laboratory techniques for soil erosion analysis" (with 19 participants).



The ICG was attended by 537 delegates from 46 countries (15 from Romania (including 7 oral presentations and 7 posters) and registered 595 abstracts out of which 380 were approved for oral presentation and 215 for poster presentation. During the conference the different thematic

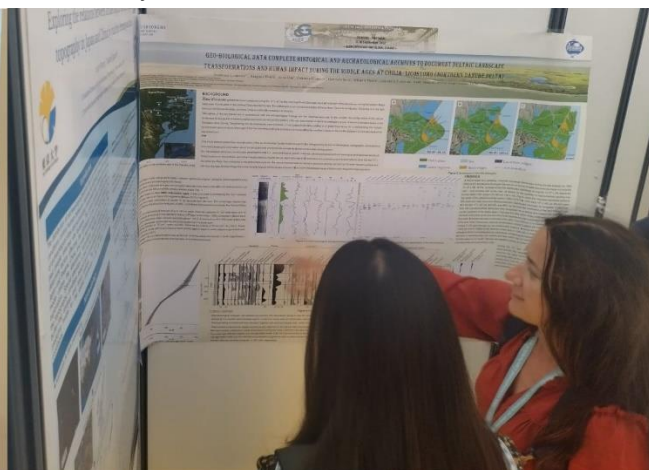
sessions were encouraged to publish their presentation in Special Issues in indexed journals. 15 collaborations of this type have been or are being negotiated, 9 of which have already been formalized (for example: Geomorphology (Forms, Processes and Landscape Change); Geomorphologie: Reliefs,

processus, environnement (Climatic Geomorphology); Zeitschrift für Geomorphologie, Global and Planetary Change (Fluvial Geomorphology). During the conference, two Council Meeting of the IAG took place (the Romanian Association of Geomorphologists was represented by Prof. Mircea



The Romanian delegation was formed by 15 delegates from 6 institutions (University of Bucharest (6), West University of Timisoara (3), The National Institute for Research and Development of Marine Geology and Geoecology – GeoEcoMar (2), Institute of Geography from Romanian Academy (2), Ștefan cel Mare University of Suceava (1), Babeș-Bolyai University (1)), which gave oral (7) and poster presentations (6) at the following sessions: Geoarchaeology (Geoarchaeological approach of the pre-historic inhabitation reconstruction of a key-region (Brăila-Jijila) from the Lower Danube Valley; Geobiological data complete historical and archaeological archives for documenting deltaic landscape transformations and human impact at Chilia-Lycostomo (Northern Danube delta); A geoarchaeological perspective on the Holocene dynamics of Someșul Mic floodplain (Transylvanian Basin, Romania)), Fluvial Geomorphology (Reducing water related risks in the Lower Danube through Nature Based Solution implementation; Annual dynamics of a river sandbar in the Lower Danube: geomorphic adjustments under anthropogenic pressures), Geomorphological Hazards and Risk Management (Epistemic uncertainties induced by landslides typology

Voiculescu, President of the association). In those meetings a new Executive Committee was elected, that will be coordinated by a new elected president in the person of Prof. Sunil Kumar De from Department of Geography, North Eastern Hill University.



in Vrancea seismic region (SE Carpathians, Romania) and their implication in hazard evaluation; A 130-year history of avalanche risk in the Fagaras Mountains, Romanian Carpathians deduced from interference with human activities⁵), Marine and coastal geomorphology (On the evolutionary patterns of the large river deltas. Examples from Danube delta and other deltaic systems; Rip currents on the Romanian Black Sea coast – distribution, characteristics and dynamics), Glacial and Periglacial Geomorphology (Permafrost distribution in the Southern Carpathians, Romania, derived from statistical modeling; Factors influencing the ground thermal regime of rock glaciers in the marginal periglacial environments of Southern Carpathians), Forms, Processes and Landscape Change (Regional debris-flow chronology reconstructed through dendrogeomorphic methods in Calimani Mountains (Eastern Carpathians, Romania)), Geomorphological Mapping, GIS, Remote Sensing and Modelling (Assessment of current and future soil erosion risk in Romania).

The next Regional Conferences on Geomorphology will be organized in Turkey between 12 to 14 September 2023 (RCG-2023 CAPPADOCIA TÜRKİYE (rcg2023.info)) and in Romania in 2025.