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## DIFFERENTIATION OF VERTICAL LIMIT OF FOREST AT THE BABIA GÓRA MT., THE WESTERN CARPATHIAN MOUNTAINS

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### Abstract

The work contains quantitative analysis of differentiation of altitudinal position and sinuosity of two lines determining the course of forest limit, i.e. timberline and treeline within Babia Góra Mt. (1725 m a.s.l.) homoclinal flysch ridge (the Western Carpathians). The course of the empiric timberline was delimited basing on aerial photographs with details from spatial data of Aerial Laser Scanning conducted in 2012. On the N slope, the course of timberline is exclusively conditioned by natural factors, whereas on the S slope this line was shifted downwards as a result of sheep and cattle grazing (however it has shown progression for the last 80 years). In the course of theoretical treeline conditioned by macrotopography and local climate, the mass-elevation effect is visible, and on the N slope, additionally, a sub-summit downward shift (the Diablak effect) occurs. The sequence of natural factors, according to their positive or negative influence on timberline and treeline courses was determined.

### Key words

timberline • treeline • mass-elevation effect • homoclinal flysch ridge • climatic asymmetry • snow avalanches • Babia Góra Mt. • Western Carpathians

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### Introduction

In the mountains, together with altitude, climatic and geomorphological conditions are getting harsher and harsher for the growth

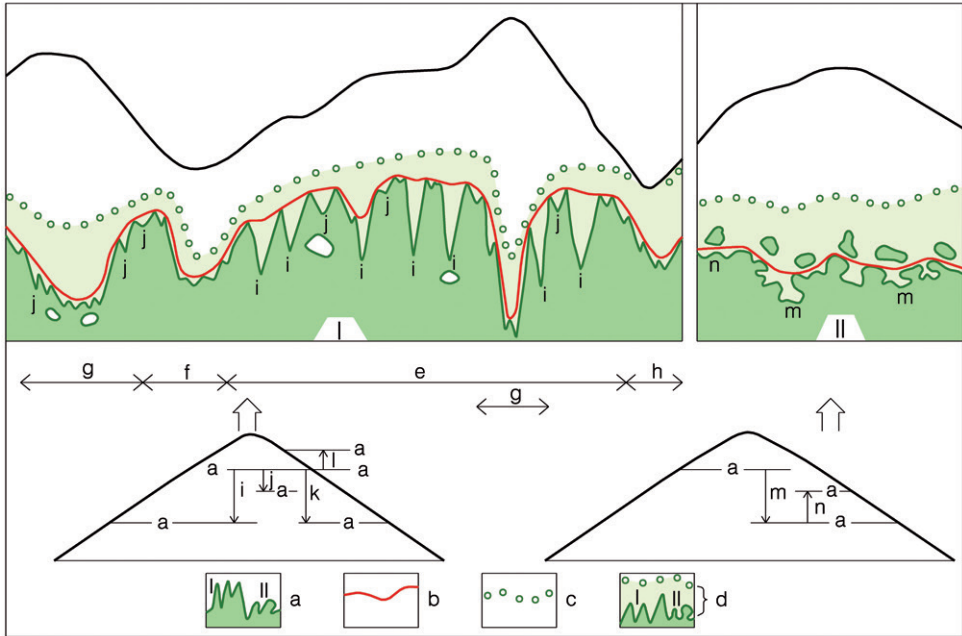
of trees and, at some altitude, a dense forest gradually changes into treeless area (Brockmann-Jerosch 1919; Däniker 1923; Troll 1973; Tranquillini 1979; Körner 2012). This boundary called forest limit is conditioned

by climate but its course is locally lowered due to relief, geomorphological processes, edaphic and hydrographical factors and human impact (Sokołowski 1928; Myczkowski 1972; Piękoś-Mirkowa 1986; Holtmeier 2009; Körner 2012). The forest limit is not a line but it is a transitional zone (ecotone) between upper montane forest and dwarf mountain pine belt. Within this zone the following lines may be distinguished: *a timberline* – empirical limit of dense forest; *a treeline* – hypothetical forest limit, the course of which is delimited by a generalised line which joins the highest located patches of dense forest; and *a tree species line* delimiting the highest limit of individual dwarf trees of a given species (Fig. 1). The altitudinal zone between a tree species line and a timberline is called a *tree-line ecotone* (Körner 1998; Körner & Paulsen 2004). The altitudinal range of the ecotone is conditioned by local climatic factors as well as topographic and geomorphological features of a given area (Leonelli et al. 2016). Part of the treeline ecotone located below the treeline is a place of a potential occurrence of forest in present climatic conditions supposing that there are no negative influences of other factors, especially geomorphological ones.

It is pointed out in the literature that macrotopography of high elevated mountain massifs of large orogeny volume (so-called *mass-elevation effect*) favours the location of timberline and treeline higher than in case of massifs with deep valleys and passes (De Quervain 1904; Turner 1961; Han et al. 2012; Zhao et al. 2014; Czajka et al. 2015) (Fig. 1). Moreover, in valley heads of shaded exposure, timberline and treeline show lower location due to local climate conditioned by topography (so-called *valley phenomenon*) (Sokołowski 1928; Myczkowski 1972; Holtmeier 2009). Similar situation occurs also beyond valley heads, at the foothills of precipitous slopes of shaded exposure, e.g. in the northern part of Giewont Mt. in the Tatras – the Western Carpathians (Piękoś 1968). This phenomenon occurs also at the leeward side of deep passes.

Timberline is locally shifted downwards in relation to treeline mainly as the result of the influence of high-magnitude geomorphological processes, like snow avalanches and debris flows, leading to mechanical destruction of forest (Fig. 1) (Butler & Walsh 1994; Walsh et al. 1994; Mock & Birkeland 2000; McClung & Schaerer 2006; Kulakowski et al. 2016; Łajczak & Spyt 2016; Rączkowska et al. 2016; Voiculescu et al. 2016). Together with the increase of altitude, the growth and development conditions of trees get more and more influenced by slope microrelief, edaphic factors, duration of snow cover, prevailing wind direction and its velocity. Slope microrelief influences the differentiation of microclimate, soil thickness, soil permeability, which all result in more twisting course of timberline (Friedel 1967; Pauker & Seastedt 1996; Holtmeier 2009). The altitudinal position of timberline also depends on physical and chemical properties of soils, which, themselves are conditioned by slope microrelief. For example, higher content of calcium carbonate favours higher altitudinal position of timberline and treeline (Sokołowski 1928; Henning 1974).

Human impact is an important factor influencing the forest limit which leads to downward shift of timberline (Holtmeier 2009; Czajka et al. 2015; Treml & Migoń 2015). This shift of timberline, and as result, also a treeline, leads to the increase of twisting character of these lines, which is caused by sheep and cattle grazing (Plesnik 1978; Piermattei et al. 2012; Shaoliang & Ning 2013; Weisberg et al. 2013), trees and shrubs logging (Sokołowski 1928; Kuemmerle et al. 2009; Knorn et al. 2012), and air pollution (Bytnerowicz et al. 2004; Kolář et al. 2015; Treml & Migoń 2015). At present, human activity in the mountains conditions the secondary succession of upward shifts of timberline (Carlson et al. 2014), which is the result of land abandonment by humans (Tasser & Tappeiner 2002) and forest protection (Vermola et al. 2004). Finally, the land abandonment has resulted for example in the Carpathian Mountains in timberline upward



**Figure 1.** Schematic course of timberline (a), treeline (b), tree species line (c) and treeline ecotone (d) on the slopes of mountain massif influenced by natural factors (I) and on the slopes where human impact caused downward shift of these lines (II). Extent: e – mass-elevation effect, f – valley effect, g – the Sarnia Skala effect (in the case of Babia Góra Mt. the Diablak effect), h – pass effect (f-h) – slopes of shaded exposure, i – deep downward shift of timberline due to the influence of height-magnitude geomorphological processes, j – shallow downward shift of timberline due to the creeping of block covers, unfavourable edaphic and hydrographic conditions, k – downward shift of timberline due to katabatic winds, l – upward shift of timberline due to anabatic winds, m – downward shift of timberline due to direct or indirect human impact, n – upward shift of timberline as a result of land abandonment by humans and forest protection up the altitude accordant with environmental conditions

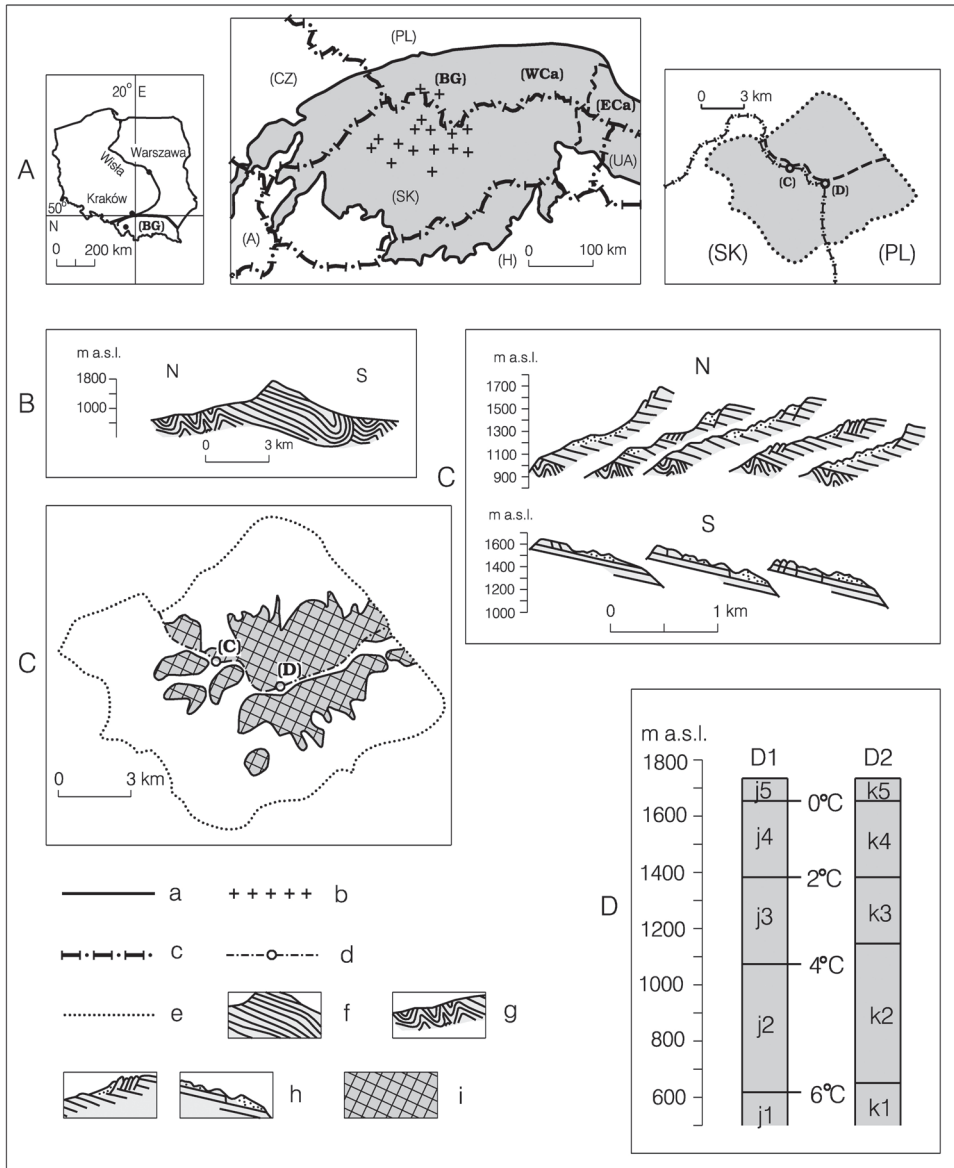
Source: Partly according to Sokołowski (1928), Myczkowski (1972), Holtmeier (2009).

shift in the rate of 9 m/decade for the last 70 years (Czajka et al. 2015).

## Study site

Babia Góra Mt. (1725 m a.s.l.) is 10 km long homoclinal asymmetric ridge, orientated W-E, reaching 1100 m of relative height. It is the highest elevated massif in the flysch Western Carpathians where the forest limit occurs (Fig. 2A). The ridge above 1000 m a.s.l. is built of layers of Magura sandstone which dip at 20° to the south. The lower parts of the ridge are built of less resistant Sub-Magura layers (Fig. 2B) (Książkiewicz 1983). The

northern slope shows concave profile and its upper part represents a precipice of the relative height of 500 m. The southern slope shows convex profile and its inclination above 1400 m a.s.l. is close to the dip of sandstone layers. The slopes built of Magura sandstone are modelled by deep-seated landslides (Łajczak 2014; Łajczak et al. 2014) where ridge and slope trenches, rock walls and headwalls occur, and lower on the slope there are block or debris colluvia formed as vast ramparts and tongues (Fig. 2C). On the N slope, valley headwater areas reach the altitude of 1100-1300 m a.s.l., whereas on the S slope they occur up to 1400 m a.s.l. Valleys cut the



**Figure 2.** Study area. A - location of Babia Góra Mt. (BG) in Poland and the Western Carpathians, limit of Babia Góra Mt., B - schematic geomorphological and geological profile (N-S), C - examples of slope profiles with deep-seated landslides, and the altitudinal extent of these landslides in the mountain, D - altitudinal range of climatic (D1) and vegetation (D2) belts. A - limit of the Carpathians (border between the Western Carpathians WCa and the Eastern Carpathians ECa is marked as broken line), b - massifs in the Western Carpathians elevated above timberline, c - state borders (PL - Poland, SK - Slovakia, CZ - Czech Republic, H - Hungary, A - Austria, UA - Ukraine), d - main ridge of Babia Góra Mt., summits (D - Diablak, C - Cyl), e - limit of Babia Góra Mt., f - Magura sandstones, g - sub-Magura layers, h - deep-seated landslides with thick layer of block colluvia (on N and S slopes), i - extent of deep-seated landslides. Climatic vertical belts: j1 - temperate warm, j2 - temperate cool, j3 - cool, j4 - very cool, j5 - temperate cold (border values of mean temperatures, °C, are marked); vegetation vertical belts: k1 - submontane forest, k2 - lower montane forest, k3 - upper montane forest, k4 - dwarf mountain pine zone, k5 - alpine meadows

Babia Góra Mt. slopes down to the depth of 300 m.

Five climatic and vegetation vertical belts are distinguished on Babia Góra Mt. (Hess 1965; Celiński & Wojterski 1983). The highest located two of them belong to alpine domain (Fig. 2D). The precipitation on the N slope locally reaches 1500 mm, and on the S slope 1200 mm (Obrębska-Starkel 2004). Water resources in the area of Babia Góra Mt. differ from 20 to over 35  $\text{dm}^3 \cdot \text{s}^{-1} \cdot \text{km}^{-2}$  (Łajczak 2016a). There is a subsurface circulation of water on the slopes above valley heads. This water supplies numerous springs which flow out from debris and block colluvia.

Forest limit on Babia Góra Mt. usually runs above valley heads in the areas of landslide relief covered by block and debris colluvia where slope inclination is in the range 20°-45°. Close to the forest limit there are numerous water springs or their groups, as well as bog-springs and landslide depressions with tiny lakes (Łajczak 2016a).

### **State of knowledge concerning altitudinal differentiation of forest limit on Mt. Babia Góra**

First informations concerning altitudinal differentiation of forest limit on Babia Góra Mt. were included in works of Zapałowicz (1879), Walas (1933), Celiński and Wojterski (1963, 1983) and Wojterski (1983), where attention was paid to climatic and orographic factors determining the course of this limit. According to these authors, the altitude of forest limit depends mainly on slope exposure of the massif, especially in the N-S profile. Results of these works determined the mean forest limit on Babia Góra Mt.: 1330 m a.s.l. on the N slope, and 1400 m a.s.l. on the S slope (1360 m a.s.l. on the whole massif). They also gave extreme altitudes of forest limit: 1280 m a.s.l. (under Szeroki Żleb on the N slope) and 1480 m a.s.l. (W slope of Cyl summit). Lower location of forest limit on the N slope was explained by longer duration of shading in this area and delayed melting

of a thick snow cover which both cause shortening of growing season. Results of these works paid attention to the role of prevailing winds from SW sector (Niedźwiedź et al., 1985), which, depending on the slope exposure, may favour or prevent from spruce seeding up the slope. They claimed that one of the causes of the downward shifted forest limit on the N slope were rapid katabatic winds. The quoted authors indicated the downward shifted course of forest limit in places where snow avalanches or rockfalls had occurred. They also paid attention to the lowered forest limit on the S slope as a result of former sheep and cattle grazing.

Detailed investigations on forest limit at Babia Góra Mt. were carried out by Zientarski (1976, 1989) and Holeska and Szwagrzyk (2005). Cited authors precisely determined the course of this limit, analysed factors conditioning its position with their detailed location. Investigations on forest limit in Slovak part of the massif were carried out by Vorčák et al. (2006a,b) and Vorčák and Jankovic (2009) and concerned the spruce restocking in timberline ecotone, which used to be a sheep and cattle grazing area. According to Jodłowski (2007) the forest limit on Babia Góra Mt. lines up with lower limit of dwarf mountain pine, which depends on local slope morphology and intensity of geomorphological processes.

Recently, investigations on geomorphological conditions of forest limit on Babia Góra Mt. have started. Czajka et al. (2015) studied morphometric aspect of timberline course in relation to macrotopography of the massif and to location and intensity of snow avalanches using LiDAR spatial data and dendrochronological investigations. In works of Łajczak et al. (2015) dominating influence of snow avalanches on local downward shift of timberline on Babia Góra Mt. was shown. Łajczak and Spyt (2016) analysed this problem in details taking into account the shape of slopes and geometric parameters of avalanche tracks.

Information concerning the downward shifted timberline course on Babia Góra

Mt. as a result of former sheep and cattle grazing (mainly on the S slope) and also as a result of former forest management locally reaching the forest limit is included in work of Łajczak (2016b). The forest limit on the steep, more geomorphologically active N slope of the massif is considered to be undisturbed by human impact on most of its course (Celiński & Wojterski 1983). At present, the investigations concern changes in timberline altitudinal position with dominating progressive trend (Czajka & Kaczka 2014a,b; Czajka et al. 2015) which intensified after establishing the Babiogórski National Park and Slovak nature reserve (Štátna prírodná rezervácia Babia hora), when sheep and cattle grazing finally finished in this massif.

In the literature there is lack of a complex approach to timberline and treeline issue on Babia Góra Mt., related to abiotic and biotic components of environment. At present such analysis is possible due to appropriate recognition of all the elements of abiotic environment of this massif, especially geomorphological, hydrographical and edaphic factors (Łajczak 2016a; Łajczak et al. 2014, 2015; Łajczak & Spyt 2016).

The aim of the work is quantitative explanation of altitudinal differentiation of timberline and treeline on Babia Góra Mt. and their sinuosity. The work is focussed on relationships between the course of both lines and morphometry and morphology of slopes and location of morphological processes which most affect the relief of the massif.

### Methods of timberline and treeline determination and cartometric calculations

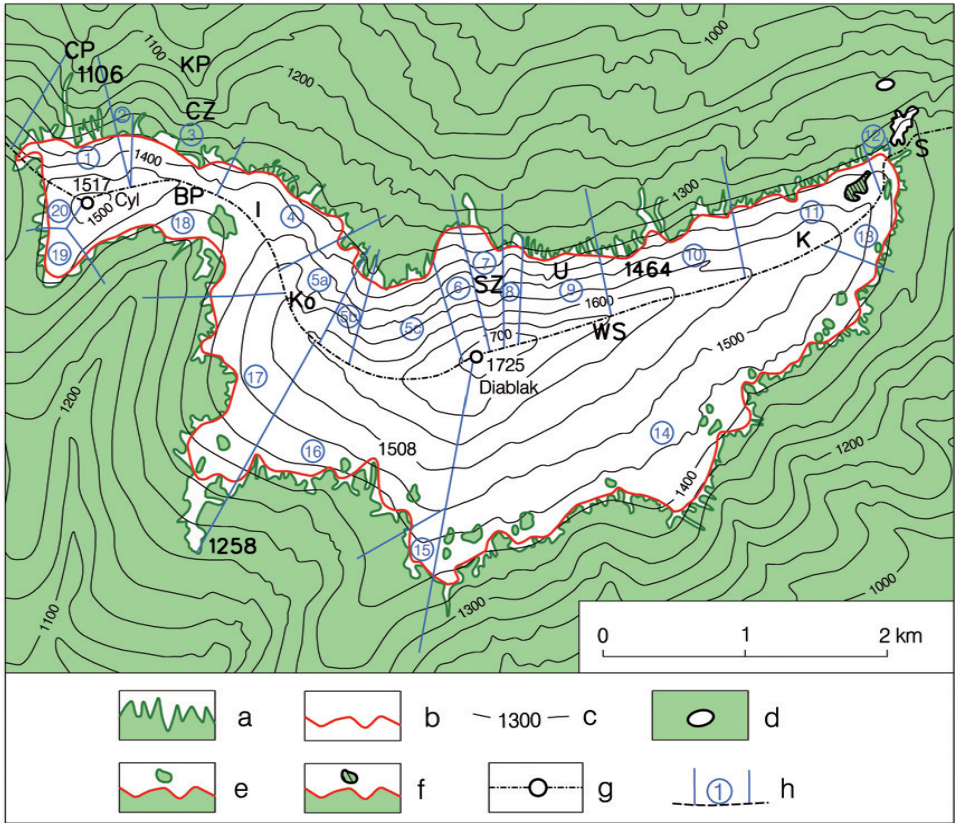
In delimiting the course of treeline and timberline on Babia Góra Mt. the methods of Guzik (2008) referring to Sokołowski (1928) were applied. They assume that the forest within timberline should show crown density > 40% and tree height > 8 m. 'Rowan copses' (*Athyrio-Sorbetum*) occurring on the N slope of Babia Góra (Parusel et al. 2004) were not taken into account in this research. Basing

on these assumptions and using orthophotomaps generated from aerial photographs (2009), photointerpretation was conducted and course of timberline was delimited. In 2012 its location was checked and elaborated using spatial data from Aerial Laser Scanning of sub-metre accuracy. Delimiting the course of a hypothetical treeline, the method introduced by Guzik (2008 – unpublished PhD thesis, after Czajka et al. 2015) was applied. It assumes that generalised course of timberline is determined from joining its local maximum values bearing in mind that inclination angle of a line joining the succeeding values cannot exceed 45°. As a result, the obtained treeline shows more mitigated course than the timberline, which is schematically shown in Figure 1.

After imposing the courses of treeline and timberline of the Babia Góra massif on the Digital Terrain Model (accuracy < 0 cm, provided from ALS data), the following parameters of these lines on the N and S slopes and within distinguished slope segments were determined (Fig. 3): timberline length ( $L_{\text{timb}}$ ) [m], treeline length ( $L_{\text{tree}}$ ) [m], mean height above sea level ( $h_m$ ) [m a.s.l.], maximum height ( $h_{\text{max}}$ ) [m a.s.l.], minimum height ( $h_{\text{min}}$ ) [m a.s.l.] of timberline and treeline, length of contour-line at  $h_m$  altitude ( $L_{\text{cl}}$ ) [m] for timberline and treeline, and sinuosity of timberline ( $L_{\text{timb}}/L_{\text{cl}}$ ) and treeline ( $L_{\text{tree}}/L_{\text{cl}}$ ) [-].

Segments of slopes of straight, step-like, concave and convex shapes on the N and S slopes of Babia Góra Mt. were selected as study areas. Within them planar, convergent and divergent slopes were distinguished (Fig. 3). Each distinguished segment of the slope is comprised in the individual altitude range:  $h_{\text{min}}$  [m a.s.l.] – axis of the massive ridge. Information about landforms, geomorphological processes and slope covers occurring in the distinguished slope segments as well as information about groups of springs, bog-springs and tiny lakes in timberline neighbourhood were taken from literature (Łajczak 2016a; Łajczak & Spyt 2016). Also slope segments in altitude range above





**Figure 3.** Timberline (a) and treeline (b) courses on Babia Góra Mt. c – contour-lines (every 50 m), d – treeless enclaves not related to sheep and cattle grazing, e – forest exclaves (spruce wood) above treeline on the areas abandoned by sheep and cattle grazing, f – stone pine forest above treeline, g – axis of massif ridge, culminations, h – boundaries of slope segments (No. 1-20) specified in Tab. 1. Each slope segment includes individual altitude interval between the hmin timberline and the axis of the ridge. Culminations of the Babia Góra Mt.: Diablak (1725), Cyl (1517). Topographic objects mentioned in the text: SZ – Szeroki Żleb, CP – Cylowy Potok stream, KP – Klinowy Potok stream, BP – Brona Pass, I – Izdebczyska, Ko – Kościółki, K – Kępa, S – Sokolica, WS – Wołowe Skatki, U – Urwisko, CZ – Cylowa Zerwa landslide. The minimum and the maximum altitude of timberline on the N and S slopes is marked

1100 m a.s.l. exposed towards N, NE, E, SE, S, SW, W, NW were distinguished.

**Results**

**Parameters of timberline and treeline on the northern and southern slopes of the massif**

The timberline in Babia Góra massif is contained in the altitude range 1106-1508 m a.s.l.,

and the treeline in 1280-1508 m a.s.l. (Fig. 3). The altitude interval where timberline occurs (very winding line) includes upper montane forest belt dominated by spruce, and fragments of lower montane forest belt and dwarf mountain pine zone. Mean temperature in this altitude interval is from below 2°C to over 4°C (Fig. 2D). The altitudinal zone occupied by treeline ecotone is located higher and formally belongs to the mentioned three

**Table 1.** Basic morphometric and geomorphological characteristics of the studied segments of the N and S slopes of Babia Góra Mt. in the altitudinal zone between the lower limit of timberline and the ridge axis

Segment of slope (No.)	Denivelation of slope (m)	Shape of slope	Dominating landforms	Slope covers
1	411	straight (n)	a, f	i, j
2	130	step-like (o)	F	k
3	185	step-like (p)	b, f	k
4	210	step-like (o)	F	k
5a	260	step-like (o)	F	h, k
5b	290	concave (p)	C	h, l
5c	375	concave, step-like (n)	c, d, f	h, k, l, m
6	450	concave (o)	C	i
7	505	concave (n)	E	h, k
8	405	straight (o)	C	k
9	395	straight (p)	c, d	h, i, l, m
10	390	concave (p)	d, f	i, k, m
11	250	step-like (p)	c, d, f	i, k, m
12	60	concave (p)	C	h, k
13	130	convex (o)	G	i
14	430	step-like, convex (n, o, p)	B, f	i, k
15	100	convex (o)	G	i
16	300	step-like, convex (n)	F	i, k
17	292	convex (o)	f, g	i, j
18	207	convex (n)	b, f	i, j
19	45	convex (o)	F	k
20	117	straight (p)	b, f	i, j

Dominating landforms: a – headwater area (the whole area plus the upper section of the stream), b – upper part of slopes of headwater area, c – rock walls, scree heaps below, d – couloirs on rock slopes, torrential cones below, e – wide corrosion trough, swell of block colluvia below, f – deep-seated landslides (ridge and slope trenches, rock walls, rocky main scarps), g – smooth slope. Slope covers: h – bare rock, i – thin debris covers, j – debris and blocky colluvia (occurring locally), k – debris and blocky colluvia (widespread occurrence), l – debris of scree heaps, m – deposits of torrential cones. Additional remarks concerning the shape of slopes: n – convergent slope, o – divergent slope, p – planar slope.

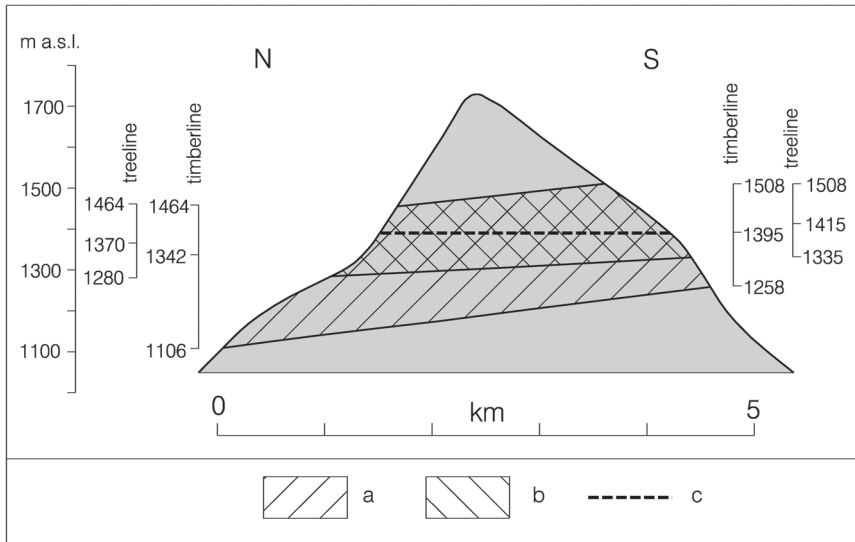
vegetation belts. The altitude range where treeline occurs includes the upper montane forest belt and dwarf mountain pine zone only.

Timberline on the N slope is located within the altitude interval 1106-1464 m a.s.l., and on the S slope within 1258-1508 m a.s.l. Mean height of timberline on the N slope is 1342 m a.s.l. and on the S slope 1395 m a.s.l. Treeline runs on Babia Góra Mt. in the following altitude intervals: on the N slope 1280-1464 m a.s.l., and on the S slope 1335-1508 m a.s.l. Mean height of treeline is on the N slope 1370 m a.s.l. and on the S slope

1415 m a.s.l. (Fig. 4). Sinuosity of timberline is larger on the N slope and it amounts to 2.96 (on the S slope 2.18). Sinuosity of treeline is similar on both slopes (S slope – 1.13, N slope – 1.14).

The presented parameters of timberline and treeline reveal asymmetry in their courses in N-S profile of Babia Góra Mt., which is mainly conditioned by climate, and in case of minimum altitudes of timberline on the N slope it is also conditioned by more intensive geomorphological processes in this area. Mean altitude of timberline and treeline





**Figure 4.** Mean, maximum and minimum altitude [m a.s.l.] of timberline and treeline on the N and S slopes of Babia Góra Mt. Altitude zones where: a - timberline, b - treeline occur, c - altitude of mean annual temperature of 2°C. Simplified profile of the massif

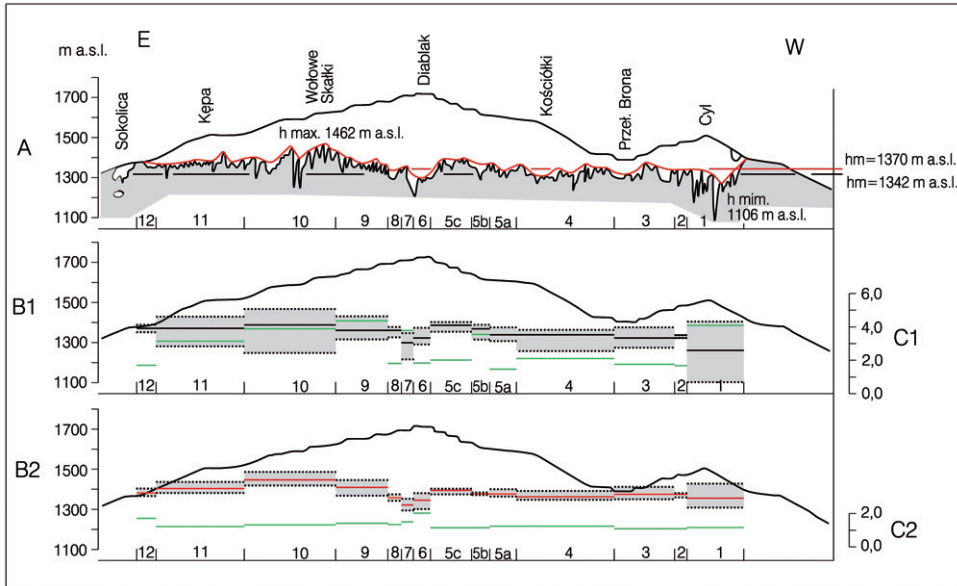
on the N slope of Babia Góra Mt. is lower than 1395 m a.s.l. which is linked to isotherm 2°C as a typical for forest limit on the Babia Góra Mt. (Hess 1965; Obrębska-Starkel 2004). On the S slope of Babia Góra Mt., mean altitude of timberline is 1395 m a.s.l. and mean altitude of treeline is 20 m higher. The occurrence of fragments of treeline and especially timberline much lower than the indicated altitude evidences the effective lowering of forest limit on Babia Góra Mt. in relation to the height of its thermal occurrence, mainly due to geomorphological processes modelling this mountain and particularly its N slope. On the other hand, the occurrence of timberline fragments over 1395 m a.s.l. on gently inclined S slope with former sheep and cattle grazing may indicate the preservation of former sections of this line which has not been changed by human activity. This information may also indicate the altitude of thermally conditioned forest limit on the S slope of Babia Góra Mt. exceeding 1395 m a.s.l., but this however was not suggested in literature. This hypothesis may be however confirmed by the discovered

in the last 50 years timberline progression on the post-shepherding areas of the S slope of Babia Góra Mt. (Czajka et al. 2015).

### Timberline and treeline courses in relation to landforms

12 slope segments (segment No. 5 contains 3 sub-segments) of straight, step-like or concave profiles were distinguished on the N slope of Babia Góra Mt, whereas on the S slope 8 segments of prevailing convex profile (Tab. 1, Figs. 3, 5, 6).

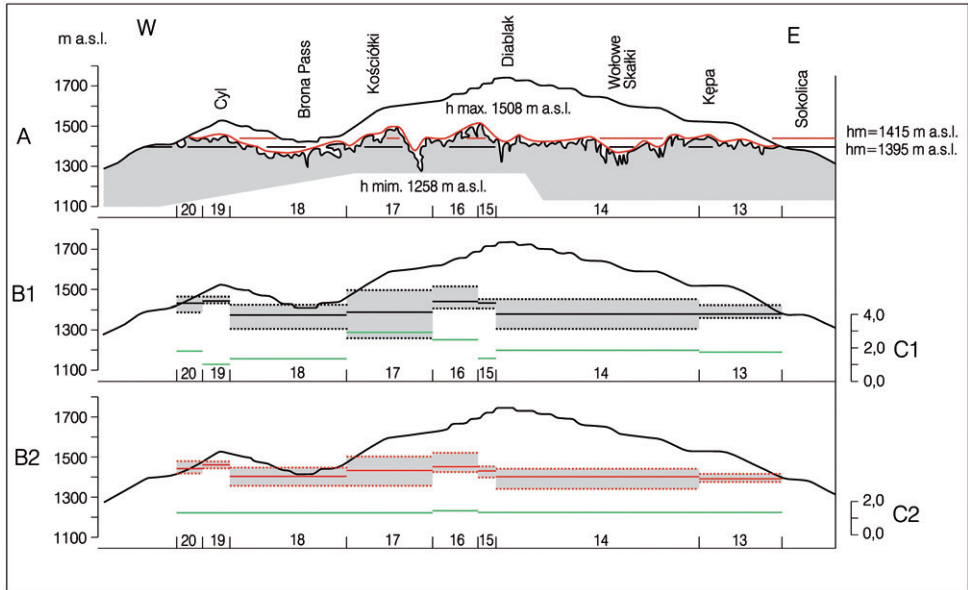
On the N slope of Babia Góra Mt., segment No. 1 comprises a headwater area of the Cylowy Potok stream and the upper part of its valley. The slopes of the headwater area show straight profile and are locally modelled by landslides. The slope segments No. 2-4 modelled by deep-seated landslides occur on the northern side of Brona Pass and the area named as Izdebczyska. These segments comprise rock walls, show step-like profile and are covered by block colluvia. The slope segment No. 5 comprises a glacial corrie. The western slope of the corrie



**Figure 5.** Course of timberline and treeline on the N slope of Babia Góra Mt. shown in horizontal projection on the background of the massif ridge profile. A – course of timberline (in black) and treeline (in red) based on Fig. 3. Maximum (hmax) and minimum (hmin) altitudes of timberline as well as mean (hm) altitude of timberline and treeline [m a.s.l.] are marked. Limit of the 12 studied slope segments and numbering of slope segments as in Fig. 3 and Tab. 1. B1 – mean (in black), maximum and minimum (dots line) altitudes of timberline in the individual slope segments. B2 – mean (in red), maximum and minimum (dots line) altitudes of treeline in the individual slope segments. Sinuosity of timberline (C1) and treeline (C2) in individual slope segments (in green). The names of topographic objects on the ridge axis are marked (as in Fig. 3)

(No. 5a, below the area named as Kościółki) contains rock walls with thick cover of block colluvia. The corrie slopes located towards the east (No. 5b and 5c) contain deep-seated landslides with rock walls and rock slopes with couloirs, debris heaps and torrential cones. Further to the east, the segments of the N slope of Babia Góra Mt. (No. 6-10) of straight or concave profiles reach the largest denivelations (390-505 m above timberline to the ridge axis) and are formed as rocky slopes of 40° (locally 70°) inclination containing couloirs, corrosion troughs, torrential cones, and locally landslides. These segments of the N slope occur below the massif culmination (Diablak, 1725 m a.s.l.) and Wołowe Skalki summit tors and comprise, among others, Szeroki Żleb (huge corrosion gully) and the area named as Urwisko (very

steep slope, about 50°-60°). The next segment of the N slope (No. 11) located below Kępa, with couloirs and landslide landforms, is more gently inclined and shows a step-like profile. Segment No. 12 is represented by Sokolica rock wall with block colluvia at its foot. In the neighbourhood of this slope segments, there is a woodless enclave including a rock wall and another woodless enclave located 150 m below in upper montane forest (Fig. 3). Almost all the studied segments of the S slope of Babia Góra Mt. show convex profile above lowermost limit of timberline. Only slope segments No. 14 and 16 embracing the upper parts of vast headwater areas modelled by deep-seated landslides, locally show step-like profile reaching the axis of the massif ridge. Slope segment No. 20 shows straight profile. On the S slope of Babia



**Figure 6.** Course of timberline and treeline on the S slope of Babia Góra Mt. Comments as in Fig. 5. Limit of the 8 studied slope segments and forest exclaves are marked at A, B1-C1 and B2-C2.

Góra Mt. there are no woodless enclaves below timberline, but there are numerous forest exclaves above treeline reaching 1450 m a.s.l., and locally 1500 m a.s.l. (Fig. 3). Among 20 slope segments of Babia Góra Mt. (segment No. 5 contains 3 sub-segments), 4 show straight profile, 5 – step-like profile, 6 – concave profile and 7 – convex profile. 5 of the distinguished slope segments represent convergent slopes, 9 – divergent slopes, and 7 planar slopes, and the longest slope (No. 14) contains in turns convergent and divergent slopes.

The courses of timberline and treeline superimposed in horizontal projection on the profile of Babia Góra Mt. (Figs. 5, 6) show better than Fig. 3 relations between their altitude and the axis of the mountain ridge. On the N slope, mean altitude of timberline in individual slope segments increases from the western and eastern parts of the slope towards its centre where it reaches 1374 m a.s.l. (Fig. 5B1; Tab. 2). However, on this slope below the massif culmination at the base of Szeroki Żleb corrosion gully, mean altitude of timberline

decreases to 1294 m s.s.l. In case of the largest altitudes of timberline in individual sections of the N slope, such regularities are not visible. On the other hand, the smallest altitudes of timberline in individual sections of the N slope show an increasing trend only from the western part of this slope towards the base of the massif culmination.

Also mean altitude of treeline on the N slope of Babia Góra Mt. increases from the west and east towards the centre of the massif where it reaches 1429 m a.s.l. (Fig. 5B2; Tab. 3). But below the massif culmination, it decreases in the slope segments No. 6-8, and at the base of Szeroki Żleb corrosion trough it amounts to 1308 m a.s.l. The maximum altitude of treeline in individual segments of the N slope does not show such regularities as in case of mean altitude. The maximum altitude of treeline was found in segment No. 10 (1464 m a.s.l.). The minimum altitudes of treeline in individual segments of the N slope, similarly to mean altitudes, increase from the west and east towards the centre of the slope to altitude

**Table 2.** Timberline parameters in the studied segments of N and S slopes of Babia Góra Mt.

Segment of slope No.	Mean altitude hm m a.s.l.	Maximum altitude hmax m a.s.l.	Minimum altitude hmin m a.s.l.	Sinuosity -
1	1269	1410	1106	4.3
2	1348	1350	1340	1.9
3	1336	1380	1290	2.0
4	1343	1375	1295	2.3
5a	1340	1315	1285	1.6
5b	1354	1375	1335	3.3
5c	1376	1395	1350	2.1
6	1314	1370	1275	1.9
7	1294	1325	1225	3.7
8	1348	1355	1325	1.9
9	1349	1405	1305	4.5
10	1374	1464	1255	4.1
11	1363	1420	1295	3.0
12	1362	1380	1340	1.7
13	1386	1410	1365	2.0
14	1384	1440	1275	2.1
15	1421	1435	1400	1.5
16	1434	1508	1390	2.7
17	1381	1490	1258	3.1
18	1377	1430	1315	1.5
19	1440	1460	1405	1.2
20	1435	1460	1390	2.0

1375 m a.s.l. Directly at the base of massif culmination (i.e. below Szeroki Żleb corrosion trough), they decrease to 1280 m a.s.l.

On the southern slope of Babia Góra Mt., the increase of mean altitude of timberline also occurs in the succeeding segments of this slope towards the massif summit, where it reaches 1434 m a.s.l. in segment No. 16 (Fig. 6B1, see Tab. 2). However the timberline reaches its highest mean altitude in the western part of this slope in segment No. 19 (1440 m a.s.l.). In contrast with the N slope, the maximum altitude reached by timberline on the S slope increases from the east and west towards the base of massif culmination where it reaches 1508 m a.s.l.

Differentiation of treeline altitude on the S slope of Babia Góra Mt. shows analogy to timberline. Mean altitude of treeline in the individual segments of the slope increases

towards the summit base to 1443 m a.s.l. (Fig. 6B2, Tab. 3) and in the most western segments reaches 1450 m a.s.l. Maximum altitude of treeline on the S slope also increases towards segment No. 16, where it reaches 1508 m a.s.l. The course of minimum altitude of treeline on this slope results from former sheep and cattle grazing.

Timberline and treeline show significant differentiation of their altitude occurrence on the N slope than on the S slope of Babia Góra Mt. This concerns both the mean values, maximum values and minimum values related to the distinguished segments of the massif slopes. The difference between the established extreme values of mean altitudes of timberline is 82 m on the N slope and 63 m on the S slope (Tab. 2). In case of maximum altitudes of timberline, the difference on the N slope is 149 m and on the S slope 147 m and in case of minimum

**Table 3.** Treeline parameters in the studied segments of N and S slopes of Babia Góra Mt.

Segment of slope No.	Mean altitude hm m a.s.l.	Maximum altitude hmax m a.s.l.	Minimum altitude hmin m a.s.l.	Sinuosity -
1	1343	1410	1300	1.2
2	1348	1350	1330	1.1
3	1358	1390	1330	1.1
4	1356	1375	1325	1.2
5a	1370	1390	1360	1.2
5b	1372	1395	1370	1.1
5c	1380	1415	1375	1.1
6	1330	1345	1285	1.9
7	1308	1320	1280	1.4
8	1340	1350	1320	1.3
9	1389	1420	1350	1.3
10	1429	1462	1372	1.1
11	1384	1415	1360	1.1
12	1360	1380	1350	1.5
13	1392	1415	1385	1.1
14	1403	1440	1340	1.1
15	1425	1430	1400	1.1
16	1443	1508	1420	1.2
17	1418	1490	1355	1.1
18	1395	1420	1350	1.1
18	1450	1460	1420	1.1
20	1443	1460	1400	1.1

altitudes of timberline is 244 m and 147 m. The difference between extreme values of mean altitudes of treeline is 121 m on the N slope and 58 on the S slope (Tab. 3). The difference of maximum altitudes of treeline reaches 142 m on the N slope and 93 m on the S slope whereas the differences of minimum altitudes of treeline reaches 95 m on the N slope and 80 m on the S slope.

The sinuosity of timberline  $L_{\text{timb}}/L_{\text{cl}}$  in the individual segments of the N slope of Babia Góra Mt. is in the range 1.65-4.5 and in the succeeding segments of the S slope in the range 1.23-3.1 (Figs. 5C1, 6C1, Tab. 2). Larger sinuosity of timberline on steeper N slope results from larger intensity of snow avalanches which locally shift downwards the course of this line (Łajczak & Spyt 2016). As opposed to the discussed earlier regularities in spatial differentiation of altitude of timberline location on both sides of the massif,

there are no such regularities in case of timberline sinuosity. On the N slope, the largest values of  $L_{\text{timb}}/L_{\text{cl}}$  exceeding 4.0 were only determined in segment of straight profile, with largest density of couloirs used by avalanches.

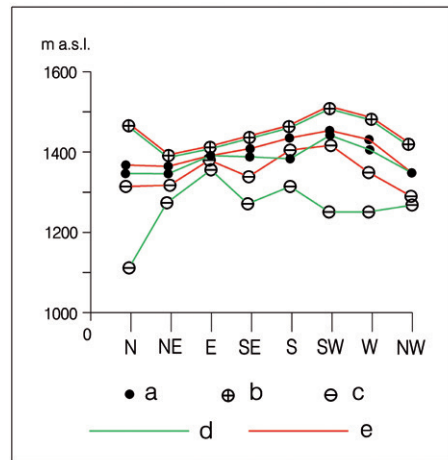
The sinuosity of treeline  $L_{\text{tree}}/L_{\text{cl}}$  in the individual segments of the N and S slopes of Babia Góra Mt. is smaller than timberline sinuosity. This parameter of treeline in the succeeding segments of the N slope is in the range 1.1-1.9 and of the S slope in the range 1.1-1.2 (Figs. 5C2, 6C2, Tab. 3). Minimum sinuosity of treeline on most of the length of the S slope results from local occurrence of snow avalanches in this area (Łajczak & Spyt 2016)

### Evaluation of the influence of natural factors on the courses of timberline and treeline

Mean temperature, insolation conditions and directions of predominating winds influence the altitude of timberline and treeline on the N and S slopes of Babia Góra Mt. The S and SW exposures of Babia Góra slopes favour the maximum altitude of timberline and treeline, where snow cover melts the earliest and the growing season is the longest. On the coldest slopes of N and NE exposures, which, in higher altitudes, have form of rockwalls with couloirs, insolation is the shortest which results in extended time of snow melting until summer (Łajczak 2004; Obrębska-Starkel 2004). The winds from S, SW and W directions predominate on Babia Góra Mt, especially of large velocity  $> 10 \text{ m}\cdot\text{s}^{-1}$  (Niedźwiedź et al. 1985). Combined influence of these climatic factors results in higher and higher mean altitude of timberline on slopes from the N, through E, S to SW exposures and from the N through W to SW exposures from 1341 to 1434 m a.s.l. (Fig. 7A). Maximum altitudes of timberline show similar differentiation. On the other hand, minimum altitudes of timberline are locally decreased on slopes of SE, S, SW, W exposure which result from former sheep and cattle grazing. Mean and maximum altitudes of treeline are similar to timberline course, however anthropogenic changes in the course of minimum altitudes of treeline are insignificant (Fig. 7B).

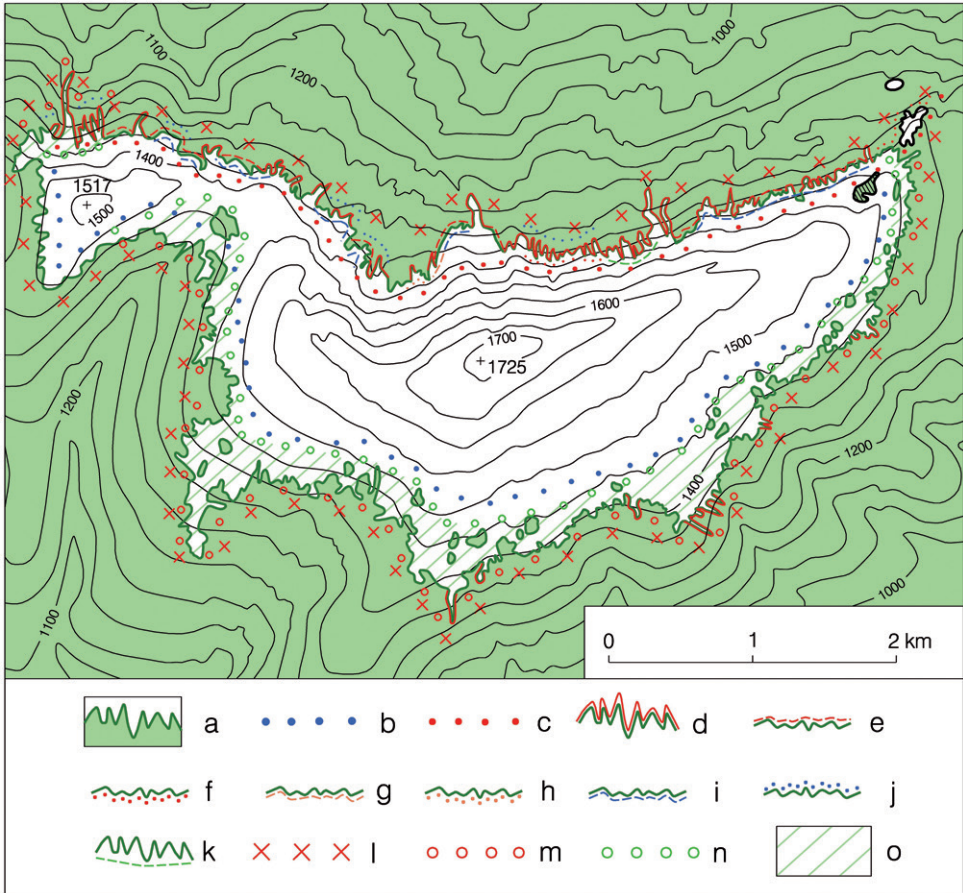
Trends of higher location of timberline and treeline from the peripheral western and eastern areas of the N and S slopes of Babia Góra Mt. towards the central areas should be considered as climatically conditioned. This difference of treeline altitude reaches 90 m on the N slope. Another effect of local climate on the N slope of Babia Góra Mt. is lowering of timberline and treeline (by 80 m) on small area with the longest duration of shading caused by the massif summit (Fig. 5A). In this part of the slope, only one snow avalanche track occurs and it cannot be assumed as responsible for treeline lowering

(Łajczak & Spyt 2016). Also the influence of other geomorphological processes in this section of treeline should be excluded. Slope in surroundings of this avalanche track is not modelled by landslides and there are not block colluvia modelled by creeping. Figure 8 shows the range of influence of various climatic factors on courses of treeline and timberline on the N and S slopes of Babia Góra Mt.



**Figure 7.** Mean (a), maximum (b) and minimum (c) altitude [m a.s.l.] of timberline (d) and treeline (e) in slope segments of Babia Góra Mt. showing different exposures. The slope segments are not related to the slope segments shown in Fig. 3

In local scale, the timberline course on Babia Góra Mt. is most of all influenced by snow avalanches. This is shown in Figure 8 where the distribution of avalanche tracks on the background of timberline course in the massif is shown. Large number of avalanche tracks and their large length on the N slope (44 tracks) results in winding course of timberline in this area, where sinuosity of this line is the largest, locally exceeding 4.0 (Tab. 2). The longest avalanche tracks and, as the result, the largest sinuosity of timberline occur on slope segments of straight or concave profiles. On the S slope, where convex profile dominates, there are only 13 short avalanche tracks above timberline, and therefore timberline sinuosity in the succeeding



**Figure 8.** The range of influence of different natural and anthropogenic factors on timberline occurrence (a) on Babia Góra Mt. Upward shift (b) of timberline due to positive influence of climatic factors (more intensive insolation, longer growing period, anabatic winds), downward shift (c) of timberline due to negative influence of climatic factors (less intensive insolation, longer duration of snow cover, katabatic winds). Downward shifted course of timberline in places of intensive geomorphological processes (negative impact): d – on avalanche tracks, e – in places of block cover creeping, f – below rockfalls, g – in places with debris flows, h – in places with shallow debris sliding. At present factors (g-h) do not shift timberline downwards. Timberline sections of downward shifted course due to additional influence of: i – edaphic factors, j – hydrographic factors; k – high position of timberline due to, among others, positive influence of edaphic factor; l – probable limit of timberline, which altitude may be temporarily shifted downwards as a result of spruce dieback due to bark beetle gradation (non-synchronous effect in individual sections of this line); m – timberline sections of downward shifted altitude as a result of sheep and cattle grazing, n – probable altitude of timberline (mainly the S slope) before the introduction of sheep and cattle grazing, o – altitudinal zone which will probably undergo spruce forest succession on post-shepherding areas

segments of the slope usually does not exceed 2.5. Larger intensity of avalanches on the N slope results in the occurrence of long timberline section below 1395 m a.s.l. (much

longer than on the S slope) coinciding with the course of isotherm 2°C. The lowest position of timberline on the N slope is 1106 m a.s.l., whereas on the S slope 1275 m a.s.l.



The decreased altitude of timberline and treeline is also determined on the slopes of Babia Góra Mt where creeping of block covers is found. This process, observed in the segments of the N slope of step-like profiles includes small areas, e.g. Kościółki (Fig. 8).

Rockfalls only locally and in minimum extend influence the course of timberline on Babia Góra Mt. Fresh, small rockfalls are observed in straight or concave profiles of the N slope (e.g. on woodless walls of Sokolica and Urwisko), causing only breakage of individual trees. In the past, rockfalls in Sokolica rock wall used to be much larger, such as the located below block field which represents a woodless enclave (Fig. 3).

Shallow-seated landslides develop mainly on the N slope of the massif in the forest belt (e.g. Cyrłowa Zerwa landslide, location in Fig. 3) and locally in dwarf mountain pine belt and therefore they do not influence the course of timberline. As a result of systematic retreat of the landslide main scarp a narrow woodless zone may develop which will reach the timberline. A probable consequence of this situation is extension of avalanche tracks below the timberline down to the bottom of the Klinowy Potok headwater area. Taking into account the range of Cyłowa Zerwa landslide, the timberline in this area may decrease below 1106 m a.s.l. which will represent a new altitudinal minimum for this line on Babia Góra Mt.

Fossil and contemporarily developing debris flows present on the N slope of Babia Góra Mt. show larger lengths than debris landslides. Some of debris flows exceeded the timberline and entered the upper montane forest. The longest debris flow which developed in June 2002 is 800 m long (Łajczak & Migoń 2007). Despite large amount of rocky material transported along this debris flow from the altitude of about 1600 m a.s.l., the adjacent timberline has not been shifted downwards.

Edaphic factors together with hydrographic factors influence both-way the altitude of timberline course on Babia Góra Mt. Small thickness of soil cover on block colluvia or its

lack, together with ground mobility (creeping) cause local downward shift of timberline on slopes of landslide morphology (segments of N slope of step-like profile, Fig. 8). Opposite situation occurs on steep segments of N slope (40-45°) of straight or concave profile (No. 9, 10) without landslides, where timberline is shifted upwards even 122 m above its mean altitude, i.e. 1464 m a.s.l. (Figs. 3, 5A). Such situation is possible due to groundwater seepages on marly insertion of shales in Magura sandstone, which counteract the acid reaction of soil and conditions their stabile moistening (Łajczak 2016a). Similar situation, but on larger scale occurs on the S slope, above its convex bend, where the number of seepages and springs supplied with water which has a long contact with insertion of marly shales in sandstone is larger than on the N slope (Łajczak 2016a).

Among hydrographic factors influencing timberline, the role of very wet places such as groups of springs, bog-springs and shores of tiny lakes, is significant. In places of large density of such objects, mainly in segments of slopes with landslide morphology, timberline is locally lowered (Fig. 8). This situation may be explained by spruce instability in places of large ground saturation.

Biological factors which may in near future cause downward shift of timberline on Babia Góra Mt. include mass spruce dieback which has occurred for several years due to bark beetle gradation. This process takes place in montane forest belt up to timberline (information from Babiogórski National Park). Opposite to natural factors lastingly influencing timberline which were mentioned by Körner (2012), potential downward shift of this line on Babia Góra Mt. will not occur simultaneously along its whole length, and it will be a transitional process until the new generation of forest appears.

### Forest limit changed by human impact

The presented features of timberline and treeline on the N slope of Babia Góra Mt. (except slope segment No. 1) suggest the

formation the courses of these lines exclusively by natural factors. Long-lasting sheep and cattle grazing on the S slope of the massif (Jostowa 1972; Łajczak 2016b) and the most extreme western segment of the N slope up to the ridge axis, caused downward shift of timberline locally even by 300 m. Since the shepherding finished in the mid 20th century, the progression of timberline has been observed (and as a result also the progression of treeline) (Czajka et al. 2015). On the S slope, this line has not reached the position delimited by forest exclaves reaching 1450 m a.s.l. or even more (Fig. 3), which should be considered as the remains of former upper montane forest. If it is assumed that the altitude range of these forest exclaves may approximately delimit the course of timberline on the S slope of the massif from before shepherding activity (Fig. 8), the parameters of this hypothetical line (and as result the parameters of treeline) will considerably differ from present parameters of this lines on this slope. As opposite to almost the whole N slope, where quite stable altitude position of timberline and treeline has been documented since the mid 20th century (Czajka et al. 2015), contemporary parameters of these both lines on the S slope should be recognised as transitional values, which may change due to timberline progression.

In the analysis of timberline course on the N slope, attention should be paid to local changes of this line in the slope segment No. 1 influenced by former forest management. Deforestation of slopes which approached or reached the forest limit at the turn of the 1920s and 1930s facilitated the extension of avalanche tracks in this segment of slope. The range of avalanche tracks was probably not effectively shortened by later forestation of vast clearings. Therefore in this part of the N slope, on one of the avalanche tracks, timberline reaches the lowest position in the whole massif – 1106 m a.s.l. (Fig. 3).

## Regularities of timberline and treeline courses and their conditions (discussion)

The determined range of timberline altitude on Babia Góra Mt. (1106-1508 m a.s.l.) exceeds the extreme values of forest limit in this mountain (1280 and 1480 m a.s.l.) given by Celiński and Wojterski (1963, 1983) because it includes now narrow woodless zones or zones occupied by forest and not considered in previous studies but now possible for detailed location using LiDAR data. At present, timberline on Babia Góra Mt. occurs about 10 m higher than in 1960, i.e. at the altitude 1375 m a.s.l. (Celiński & Wojterski 1963), which indicates progression of timberline after finishing sheep and cattle grazing in this area. The determined by the Authors contemporary mean altitudes of timberline as 1375 m a.s.l. and treeline as 1406 m a.s.l. on Babia Góra Mt. are close to 1395 m a.s.l. which is the altitude of the course of isotherm 2°C in this massif (Obrębska-Starkel 2004). This temperature value is assumed as a limit value delimiting the altitude range of forest in the Western Carpathians (Hess 1965).

In this work, the attention was paid for the first time to a deep depression of timberline, partly conditioned by human impact, in one of the longest avalanche tracks on the N slope of Babia Góra Mt., going down to the altitude 1106 m a.s.l. within the lower montane forest belt. Also the highest located point of timberline (1508 m a.s.l.) was shown within dwarf mountain pine zone on gently inclined S slope which may inform about altitudinal position of this line on this slope before the shepherding had started in the 17th century. The spread of timberline altitude on Babia Góra Mt. of 402 m is larger than in the Polish Tatra Mountains (350 m: Piękoś-Mirkowa, Mirek 1996) and in the whole massif of the Karkonosze Mountains (290 m: Tremł & Migoń 2015).

In growing season, the altitude of treeline on Babia Góra Mt. is influenced by climatic factors (area solar radiation, mean temperature, prevailing wind directions, length

of growing season). For example, the high position of this line on the western slope of Cyl summit (Fig. 3) can be explained by frequent western winds (Celiński & Wojterski 1963, 1983; Wojterski 1983; Holeksa & Szważczyk 2005) and on the SW side of the Diablak summit also by western winds and additionally by the warmest exposition of the slope (Czajka et al. 2015). Such influences result in asymmetry of mean, maximum and minimum altitudes of treeline between the N and S slopes of Babia Góra Mt., which amounts to 45 m favouring the S slope. In the altitude interval occupied by treeline, the area solar radiation in growing season amounts to 666 kWh·m<sup>-2</sup>, whereas on the S slope to 959 kWh·m<sup>-2</sup> (Czajka et al. 2015). The highest location of treeline on Babia Góra Mt. was determined on slope segments of SW exposure, and the lowest location on slopes of N exposure, which results from the combined influence of thermal conditions, insolation conditions and wind directions. These results differ from the results of similar investigations in the Tatra Mountains (Sokołowski 1928; Piękoś-Mirkowa & Mirek 1996), where the lowest located forest limit was determined on the slopes of E exposure.

The following regularities of timberline and treeline courses on the N and S slopes of Babia Góra Mt. have been determined:

(1) Mean altitude of these lines (within the studied slope segments) show increasing trend from extreme parts of slopes towards the base of massif summit, which reflects more favourable climatic conditions for higher altitudinal position of forest limit in the central part of the massif, which is not dismembered in this area by deep valleys. This situation confirms a regularity called *mass-elevation effect* (De Quervain 1904; Turner 1961; Han et al. 2012; Zhao et al. 2014; Czajka et al. 2015). Treeline in the central part of the N slope is located up to 90 m higher than in the marginal parts of this slope. In the case of the S slope this difference reaches 50 m. In the Tatras, in the central part of the N slope, the forest limit reaches 200 m higher

than in peripheral parts of this slope (Pawłowski 1972).

(2) On the steep N slope of Babia Góra Mt. below massif culmination (Diablak), which is the place of the longest duration of shading, mean altitude of timberline is shifted downwards by 80 m. This situation, named by the Authors *Diablak's effect* should be recognised as an analogue to the lowering of forest limit at the foot of high and precipitous slopes of shaded exposure. For example, on the north side of Giewont Mt. (1894 m a.s.l.) in the Tatra Mountains, the treeline is shifted downwards by 200 m (*phenomenon of Sarnia Skala*, see Piękoś 1968). On the other hand, high location of treeline on the part of S slope of Babia Góra Mt. of local SW exposure below the massif culmination is recognised as the phenomenon opposite to *Diablak's effect*, where because of most favourable thermal, insolation and anemometric conditions as well as morphometric and geomorphological conditions, the treeline reaches its maximum altitude 1508 m a.s.l. Known from literature *valley phenomenon* (Holtmeier 2009) was studied in the Polish Tatra Mountains by Sokołowski (1928) and Myczkowski (1972). In that area, at the foot of the northern slope of Mięgużowiecki Szczyt Mt. (2438 m a.s.l.) treeline is shifted downwards to the altitude of Morskie Oko Lake (1395 m a.s.l.). On Babia Góra Mt. however, because of the lack of deep valleys of northern exposure, *valley phenomenon* does not occur.

The downward shift of altitudinal position of timberline on Babia Góra Mt. is influenced by geomorphological and edaphic conditions such as: rock walls, elements of landslide relief (slips, vast fields of block colluvia), morphological processes modelling slopes (snow avalanches, creeping of block covers), locally strongly moist slope covers or slope covers with poorly developed soil profile. This is accompanied by more twisting course of timberline. Sinuosity of timberline on the precipitous N slope of the mountain with dense network of avalanche tracks is three times bigger than treeline, whereas on the gently inclined S slope it is only twice

as bigger. The lowest located point of timberline occurs on the N slope 236 m below the mean altitude of this line (which results mainly from avalanches) and the highest located point occurs 122 m above the mean altitude (influences of local slope relief and edaphic factor). On gently inclined S slope with less intensive geomorphological processes, the minimum altitude of timberline is only 137 m smaller than its mean altitude, and maximum altitude is 113 m higher than the average.

The presented results of investigations confirm the indicated in the literature (Butler & Walsh 1994; Walsh et al. 1994; Mock & Birkeland 2000; McClung & Schaerer 2006; Kulakowski et al. 2016; Łajczak & Spyt 2016; Rączkowska et al. 2016; Voiculescu et al. 2016) and also referring to Babia Góra Mt. (Celiński & Wojterski 1963, 1983; Wojterski 1983; Zientarski 1989; Holeska & Szwagrzyk 2005; Łajczak et al. 2015; Łajczak & Spyt 2016) dominating role of snow avalanches in local downward shift of forest limit. In this work the attention is paid to relation between density and length of avalanche tracks and the sinusosity of timberline and treeline. According to results obtained and opposite to the older views (e.g. Celiński & Wojterski 1963, 1983), the developing at present small rockfalls do not play an essential role in timberline downward shift on Babia Góra Mt. On the other hand, creeping of block covers was assumed as a factor which significantly influences timberline downward shift, but only within small areas of the N slope. Also the influence of shallow-seated landslides and debris flows has not been taken into consideration at Babia Góra Mt., as these geomorphological processes have activated for the last 20 years. In foreign literature, attention is paid to an important role of debris flows on slopes in local lowering of timberline (Butler & Walsh 1994; Walsh et al. 1994; Mock & Birkeland 2000; McClung & Schaerer 2006). The observations of the Authors indicate, that movement of waste-mantle on slopes of Babia Góra Mt. in form of debris flows and also shallow sliding, despite the essential changes

in the relief, does not influence the timberline. In the past, in the areas with sheep and cattle grazing, because of timberline downward shift and rarefication of dwarf mountain pine, these geomorphological processes probably started to activate, which was one of the causes of extension of avalanche tracks. This was the reason, for example, that the largest downward shift of timberline on Babia Góra Mt. occurred on the N slope of Cyl (Łajczak et al. 2015).

The attention is paid to the role of microtopography in differentiation of physical and chemical properties of soils, their watering and thickness of soil profile, which influences the course of timberline in local scale (Friedel 1967; Pauker & Seastedt 1996). Indicated in this work essential influence of edaphic and hydrographic factors on local course of timberline on Babia Góra Mt. confirms this view. This should be explained by a mosaic character of this factors conditioned by diversified morphology of landslide slopes (step-like profile, depressions and hollows). Suggested by Henning (1974) regularity, saying that higher content of calcium carbonate favours higher altitudinal position of timberline was also confirmed in this work. Highly located timberline on the steep N slope of Babia Góra Mt. is explained, among others, by the inflow of water from seepages to soils, which contacted with insertions of marly shales in the substratum (Łajczak 2016a).

The greater timberline length (88%) on the N slope of Babia Góra Mt. occurs below 1395 m a.s.l. (i.e. on the altitude with mean temperature  $> 2^{\circ}\text{C}$ ) as a result of extra-climatic factors. The other 12% of timberline length occurs above 1395 m a.s.l. On the gently inclined S slope, only 38% of timberline length occurs below this altitude and 62% occurs on higher altitude. This indicates more effective downward shift of forest limit in relation to the altitude assumed as theoretical climatic forest limit (Holtmeier 2009) influenced by geomorphological processes on the precipitous N slope of Babia Góra Mt. The results of this work confirm the opinion of Holtmeier (2009) suggesting that larger slope inclination

and smaller distance between the timberline and the ridge axis results in intensified influence of geomorphological processes on altitudinal position of timberline. He also stated that steepness of a slope does not negatively influence on altitudinal position of timberline but regulates the occurrence and intensity of high-energy mass movements, as snow avalanches for example, which locally shift downwards the timberline. This statement is also confirmed by the results of this work. This is why, according to Holtmeier (1974), forest reaches the highest altitudes on slopes without snow avalanches. In the case of Babia Góra Mt., this is indicated by the occurrence of short sections of timberline in parts of the N slope of inclination 40°-45° up to the altitude 1464 m a.s.l., however in places of stable ground (no landslides) and far from avalanche tracks.

Among the discussed forms of human impact on natural environment of the mountains (e.g. Sokołowski 1928; Billings 1969; Lauer & Klause 1975; Plesnik 1978; Bytnerowicz et al. 2004; Schickhoff 2005; Holtmeier 2009; Kuemmerle et al. 2009; Knorn et al. 2012; Piermattei et al. 2012; Shaoliang & Ning 2013; Weisberg et al. 2013; Czajka et al. 2015; Kolář et al. 2015; Tremł & Migoń 2015; Viehweider et al. 2015) only sheep and cattle grazing connected with shrubs and trees logging (Jostowa 1972; Łajczak 2016b) represent main factors which caused downward shift of timberline on Babia Góra Mt. Logging of dwarf mountain pine and spruce activated snow avalanches which caused further downward shift of timberline. Such conditioned lowering of timberline included also, mentioned earlier, small part of the N slope of the massif. The second reason of local downward shift of timberline was forestry, which, until 1930, was carried out mainly on the S slope up to forest limit (Łajczak 2016b). On the N slope of Babia Góra Mt., altitudinal location of timberline on over 90% of its length is exclusively conditioned by natural factors and does not show anthropogenic disturbances (Celiński & Wojterski 1963; Czajka et al. 2015). For 80 years, the process

of timberline revitalisation on Babia Góra Mt. has taken place, which is manifested in secondary succession and upward shift of timberline (Czajka et al. 2015) due to land abandonment by humans and forest protection. These phenomena have similar causes and course as indicated in the literature (Tasser & Tappeiner 2002; Vermola et al. 2004; Carlson et al. 2014).

Apart from biological factors influencing location of timberline suggested by Körner (2012), in the case of Babia Góra Mt., the attention should be additionally paid to presently occurring spruce dieback caused by bark beetle in the whole altitudinal range of forest belt. This process may lead to such a rarefication of spruce forest in its upper limit, that taking into account one of formal requirements of timberline delimitation, i.e. crown density > 40%, the altitudinal position of this line may be changed. Possible downward shift of timberline should be however assumed as a temporary phenomenon (as opposed to other natural factors) until new generation of forest appears.

## Conclusions

1. This work shows geometric parameters of timberline and treeline in the studied segments of the N and S slopes of Babia Góra Mt., which differ in terms of topography and landforms. The differentiation of altitude of these lines was analysed in E-W direction and their sinuosity on the N and S slopes of this mountain in relation to: (a) slope morphometry, (b) slope morphology, (c) distribution of geomorphological processes, (d) edaphic and hydrographic processes. The influence of natural processes on timberline and treeline courses was expressed in quantitative way and their location was marked in figures with examples.

2. It was shown that mean altitude of timberline on the S slope of Babia Góra Mt. is 53 m higher than on the N slope, and the altitude difference between the highest and lowest located point of this line on the whole massif is 402 m. It was shown that

on Babia Góra Mt. the course of timberline and treeline is conditioned by massif topography and it is similar to the described in literature phenomenon called *mass-elevation effect*. In this area, there is also phenomenon similar to *Sarnia Skala phenomenon* from the Tatra Mountains called by the Authors *Diablak effect*. *Valley phenomenon* was not determined on Babia Góra Mt.

3. The sequence of natural factors according to the intensity of their positive influence on the course of timberline and treeline (favouring the upward shift of these lines with altitude) on gently inclined S slope is as follows: larger area solar radiation, longer growing period, dominating winds from S, SW and W directions, smaller intensity of geomorphological processes, favouring edaphic factors. On the other hand, there is negative influence of natural factors on the steep N slope, which leads to downward shift of timberline and treeline (snow avalanches, smaller area solar radiation, short growing season, frequent katabatic winds, edaphic and hydrographic factors in local scale, creeping of block covers). Locally on the N slope, high limit of timberline and treeline is favoured by edaphic factors related to stable ground and its intensive moisture (areas without snow avalanches and landslides).

4. Creeping of block colluvia represents a geomorphological process which negatively influences timberline on Babia Góra Mt. It is apparently rarely taken into account in literature, but was taken into account in this work. The influence of this natural factor is coincidental with the influence of edaphic factors which occur on block fields grown only by lichens. In this work, a negative influence of hydrographic factors (groups of springs, bog-springs, shores of tiny lakes) on timberline was discussed for the first time. These factors usually occur on slopes with landslide relief of step-like profile. This influence is caused by poorly coherent and water saturated ground, which favours the overturning of shallow rooting spruce trees by wind. The edaphic and hydrographic factors were mentioned for the first time in this work as factors

positively influencing timberline on the steep N slope of stable ground and without the reach of snow avalanches. Summarising, the role of edaphic and hydrographic factors in formation of altitudinal position of timberline in Babia Góra massif (although in local scale) should be recognised as one of the most significant, giving way only to influences of topoclimate, snow avalanches, and block cover creeping.

5. It was shown that geomorphological processes which at present are the most important in slope modelling of Babia Góra Mt. such as shallow-seated landslides and debris flows do not influence timberline.

6. The present course of timberline and treeline on the S slope of Babia Góra Mt. was formed by sheep and cattle grazing influence which finished in this area several decades ago. It may be assumed, that in the succeeding years, together with forest revitalisation on post-shepherding areas, the courses of timberline and treeline on this slope will get smooth and even. In such situation, both lines on the S slope will run on higher altitude than now, which will make even larger contrast with the N slope, where sinusoidal course of timberline will not change much.

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Editors' note:

Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

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