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THE RECENT TIMBERLINE CHANGES IN THE TATRA MOUNTAINS: A CASE STUDY OF THE MENGUSOVSKÁ VALLEY (SLOVAKIA) AND THE RYBI POTOK VALLEY (POLAND)

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Abstract

A comparison was done of the timberline course from the mid-20th and beginning of 21st century, in Mengusovská Valley (Slovakia) and Rybi Potok Valley (Poland). These are two valleys in the High Tatra Mts. Aerial photos and satellite images were used to assess the changes of the timberline in the two valleys. The course of the timberline ecotone in both valleys is similar. In both valleys, the stable timberline section is almost half of the total timberline length. In both valleys there has been an increase in the elevation of the timberline (on average by 10 m in the Mengusovská Valley and 15 m in the Rybi Potok Valley), and free spaces have been increasingly closing up. The progressive changes of the timberline are mainly due to the limit placed on human economic activity, and to climate warming. Inactive avalanche paths have led to an enlargement of the forest area in both valleys. The reduction of avalanche activity is the direct result of climate warming in the Tatra Mts. and from the decrease in the amount of snow in winters.

Key words

snow avalanches • Carpathians • Tatra Mountains • photointerpretation • reafforestation • timberline ecotone

Introduction

The upper timberline is considered the upper elevational limit of forest in high-mountain regions all over the world, except for the Antarctic (Holtmeier 2009). It is also defined as a zone (ecotone) dividing the area of dense forest from single trees, dwarf mountain pine, juniper or low vegetation (Troll 1973; Grace 1989).

The factors controlling the elevation and type of the timberline ecotone (TE) have a global and local character. The course of the timberline ecotone is generally dependent on the climate. This factor limits the growth of the trees in the upper timberline and above it. The location of the vertical vegetation zones depends on the mountain-mass effect (de Quervain 1904; Brockmann-Jerosch 1919; Tollner 1949), and in an interrelated way, the continental effect. Apart from climatic factors, other environmental components, such as topography, lithology, morphogenetic processes, ecological factors, and human activity, control the location and character of the timberline (Brown 1994; Walsh et al. 1994; Holtmeier 2009; Jodłowski 2007; Kozłowska 2008). The ecological factors are mainly related to the competition between different species for access to sunlight, water, and minerals (Sokołowski 1928). Snow avalanches and abrupt mass movements, such as debris flows and rockfalls, directly or indirectly influence the character of the forest system (Kotarba & Starkel 1972; Chomicz & Knazovicky 1974; Kotarba et al. 1987; Rączkowska 2006). The destructive impact of mass movements and snow avalanches is the main factor lowering the course of the timberline ecotone. Many changes of timberline are human-induced. In the high mountains, mining, cattle and sheep grazing, and logging are environmental threats (Mirek 1996; Boltižiar 2007; Slaymaker & Embleton-Hamann 2009). Recently, an increasing number of tourists and the expansion of the touristic infrastructure have caused deforestation or have influenced the condition of the forests (Motta & Nola 2001; Jodłowski 2007; Weisberg et al. 2013). The indirect effect of human activity, e.g. air pollution, weakens the condition of trees and as a result insect outbreaks.

The timberline ecotone (TE) is considered to be a sensitive component of the high-mountain environment, separating the morphogenetic periglacial (cryonival) zone from the temperate forest domain (Kotarba & Starkel 1972). The changes of the components of the environment above and below the TE, are reflected in the modifications of the timberline course.

The aim of this study was to:

- define the changes of the TE course during the period when direct human impact is on the decline,
- compare the changes of the TE in high-mountain valleys with opposite exposure to the main ridge in the Tatras,
- and identify the main factors determining the changes of the TE.

Study site

The research was carried out in the High Tatra Mountains, in the Carpathians Mountains. The Rybi Potok Valley is located at the northern side and the Mengusovská Valley at the southern side of the main ridge of the Tatra Mountains. The study sites were located in:

- the middle part of the Rybi Potok Valley,
- the middle part of the Mengusovská Valley.

Both valleys are at the altitude of around 1500 m a.s.l. Although the Mengusovská Valley is bigger, the investigated areas and other geographical features are comparable (Tab. 1).

Both valleys are developed within a crystalline core, which is formed of intrusive carboniferous granitoids of the High Tatra Mts. (Bac-Moszaszwili et al 1979; Nemčok at al. 1994). The relief of both study sites is of glacial origin (Klimaszewski 1988; Lukniš 1973). The valleys are deep glacial troughs with step-like longitudinal profiles. Broad hanging glacial cirques with rocky steps up to 300 meters high are developed in the uppermost parts of the valleys. The Czarny Staw pod Rysami Lake and Morskie Oko Lake in the north, and the Vel`ké Hincovo Pleso Lake and Popradské Pleso Lake in the south are the biggest lakes in the valleys, occupying the overdeepenings at their bottoms. Steep or vertical rocky slopes with talus slopes below, are characteristic features of the valley sides, both in glacial cirques and troughs (Klimaszewski 1988; Lukniš 1973). The valleys' bottoms are filled with blocky-bouldery moraine deposits. These deposits form well preserved ridges of lateral, middle, and recessional moraine in the landscape. Streams originating from the lakes (Rybi Potok in the north, and Hincov Potok and Krupa

Table 1. The comparison of the main geographical characteristics of the two investigated valleys

	The area of the study site/ whole valley [km^2]	Forest cover area [ha]	Variance of Topographic Position Index[1]	The highest/ lowest point in the valley [m a.s.l.]	The length of the valley [km]
The Mengusovská Valley	15.6/16.0	86.8 (1949) 100.7 (2009)	591.1	2547/1405	11.4
The Rybi Potok Valley	9.9/11.5	134.4 (1955) 166.2 (2009)	890.0	2499/1096	9.4

[1] Topographic Position Index (Jennes 2006): quantitative characterisation of the relief diversity level

Potok in the south) flow at the bottom of both valleys. At present, the relief is transformed by the comprehensive set of morphogenetic processes, especially gravitational and cryonival, as well as erosional and aeolian (Kotarba et al. 1987; Rączkowska 2007, 2008; Rączkowska et al. 2012; Hreško et al. 2008). The debris flows and rock falls are the most effective (Kotarba et al. 1987; Krzemień 1988; Kotarba 1995; Hreško & Boltižiar 2001; Rączkowska 2006; Hreško et al. 2008; Kapusta et al. 2010; Kotarba et al. 2013).

In both valleys, the forest in the subalpine zone is composed of *Picea abies* L. Karst with a small quantity of *Pinus cembra* L. Above the timberline, single individuals and groups of Norway spruce and stone pine can be found. In the Mengusovská Valley, stone pine can form a compact forest. Above the upper elevational limit of the forest, there are more *Pinus mugo* L. than alpine meadows.

For hundreds of years humans have influenced the environment of the Tatras but this activity has become much more prevalent in the last 200-300 years (Harvan 1965; Midriak 1977; Mirek 1996; Gašpar 2002; Bohuš 2005; Boltižiar 2007). The most intensive changes in the timberline and dwarf mountain pine belt were influenced by logging and pasturing. These two activities were performed to acquire wood and create space for cattle and sheep pasturing. In the Tatra Mts. cattle and sheep grazing took place till end of the Second World War. In the Polish part of Tatras during this period the number of pastured animals reached more than 40 thousand. The grazing had a major environmental impact on the forests, soil erosion, and hydrology. Therefore, to protect the landscape, national parks were established (in 1955 in Poland and in 1949 in Slovakia). Logging ceased immediately but pasturing continued until the 1960s. In the last few years, the subalpine forest in the Polish Tatra Mts. has been severely damaged due to the outbreak of the bark beetle (*Ips typographus*).

Materials and methods

The primary research material consisted of contemporary satellite imagery and archival aerial photographs (Brown et al. 1994; Baker et al. 1995; Wężyk & Guzik 2004). The satellite imagery was taken in February 2009 by the GeoEye-1 satellite, DigitalGlobe in the highest resolution available for commercial satellite imagery (resolution 0.5 m; accuracy 10.2 m). The images can be accessed through the World Imagery function in the ArcMap 10.2.2 programme of the ESRI Company. The archival aerial photos of the Mengusovská Valley (the Slovakian Tatra Mts.) were taken in 1949 at a scale of 1:10,000, and those of the Rybi Potok Valley (the Polish Tatras) – in 1955 at a scale of 1:20,000. Both sets of panchromatic photos were orthorectified. The scans of the older photographs (1949) were not stereoscopic and came from paper copies, causing the digital version to have slight distortions. Despite the difficulties, the average orthorectification error at the photopoints of the orthophotomaps from 1949 and 1955 was 3.44 m and 3.95 m, respectively. That is an acceptable tracking error according to the Technical Directives K-2.7 (1999) and K-2.8 (2001). Such an accuracy allows for a reliable and precise delineation of the historical range of the upper timberline (Guzik 2008; Czajka et al. 2015).

We studied and analysed the changes of the timberline ecotone (TE), according to Sokołowski's definition (1928). The timberline ecotone is represented by an empirical biotic boundary between a dense Norway spruce forest and/or a Swiss pine forest (crown cover ≥ 0.4) with the height of trees of at least 8 m and other types of vegetation:

- single spruces,
- spruces timber atoll,
- dwarf mountain pine,
- tall herb fringe, and grassy vegetation communities.

The changes in the course of the timberline ecotone were observed in the compilation of photos from 1949 and 2009 (the Mengusovská Valley) and from 1955 and 2009 (the Rybi Potok Valley). The timberline ecotone modifications were assigned to three categories:

1. no changes in a 10 m range (the resolution of aerial photos) – a stable timberline ecotone,
2. an increase in the range of more than 10 m in comparison with the previous state (1949 or 1955) – a progressive timberline ecotone,
3. a forest decrease causing a shift of the timberline by a value exceeding 10 m – a regressive timberline ecotone.

The changes of the timberline course affected by the local changes of the forested areas were also studied. The changes of the timberline position above the threshold value of 10 m and the polygons of changes greater than 10 acres were taken into consideration (Plesnik 1973; Guzik 2008).

In the analyses of the spatial changes of the TE, digital elevation models created with the use of photogrammetric methods in a variable grid of squares from 10 m to 20 m were employed. The average vertical error of the model is -1.98 m (Guzik 2008). On the basis of the digital terrain model the exposure model was generated. The photointerpretation, digitisation, and spatial analyses were performed using the tools available in the ArcMap 10.2.2 software. The vector layers of the timberline were converted to 3D which resulted in obtaining certain spatial information. The basic parametres of the particular types of TE were calculated, including length, altitude a.s.l. (average, maximum, minimum) and the proportion in the total length of the TE in a given valley. The number, and surface area of polygons, which have increased or decreased since 1949/1955, were determined. On the basis of field observations (2009-2014), published research (including Sokołowski 1928; Kłapowa 1969; Guzik & Bukowski 2009), and thematic maps (Kłapowa 1976; Trafas 1985), 121 cases were identified in which there was a local increase in the forested surface area. This increase resulted from:

- the reafforestation of avalanche paths,
- an increased crown cover of the tree stands adjacent to the main body of the forest, or
- the forming of single patches which were classified.

Some of the changes were of a mixed nature but in some cases, it was not possible to indisputably classify them.

For the purpose of determining the geometrical complexity of the timberline, the line development index (*K*), widely used (Hutchinson 1957; Pociask-Karteczka 2006) in hydrology, was adopted.

$$K = \frac{L}{2\sqrt{\pi A}}$$

K – the line development index
L – the length of the TE line [m]
A – the surface area of the upper montane belt forest within the given borderlines, in 2D (two dimensions) [m^2]

The conducted analyses took into account the whole forested surface areas in 2009, including the areas infested by the bark beetle. The dead trees in the areas were included as forested surface areas, as a sort of simplification. The classification of such phenomena requires further research in the area of forest ecology, however, the dead trees are not the subjects of the present study. The area below the TE in the main body of the forest was treated as a whole. The changes occurring inside the forest were not analysed.

The boundaries of the study site in the lower part may seem artificial but in both cases the research area depended on the available archival aerial photographs of the Slovakian part of the Tatras.

Results and discussion

The comparison of the course of the TE in the mid-20th century and early 21st century shows certain crucial changes that have taken place in both valleys (Tab. 2). The length of the TE in the studied part of the Mengusovská Valley in 1949 reached to over 17.3 km, and in 2009 was about 0.8 km shorter (Fig. 1). In the Rybi Potok Valley, the reversed was true (Fig. 2). In 1955 the length of the TE was 17.5 km and after 54 years the length of the TE extended another 4.9 km. In the mid-20th century the forest in the Mengusovská Valley occupied an area of 86 ha, of which the main forest body accounted for 92% and the rest consisted of 9 polygons with an average surface area of 72 a (SD = 94). After 60 years, the forested surface area increased to 101 ha. The surface area of the main body of the forest, occupying the bottom and part of the slopes of the valley, rose by 17%. Only 7 forest patches, with an average surface area of 104 a (SD = 121), appear above the main body of the forest.

In the Rybi Potok Valley the forested surface area in the middle of the 20th century was 136 ha, of which the main body of the forest occupied 96%, and there were 12 polygons with an average surface area of 44.5 a (SD = 36). In 2009, the forested surface area increased to 166 ha and the spatial structure became more complex. The main body of the forest is 93% of the area, and there are 31 polygons with an average surface area of 38.7 a (SD = 34). The spatial complexity of the forest in the timberline ecotone is reflected not only in the number of forest patches located separately and having very variable surface areas, but also in the complex geometry of the timberline itself. An idealised course of the timberline refers to the course of MAAT +2°C isotherm (Hess 1965) which theoretically determines

Table 2. The main parameters of the Timberline Ecotone (TE) in 1949/1955-2009

The feature/year	The Mengusovská Valley		The Rybi Potok Valley	
	1949	2009	1955	2009
TE length [km]	17.3	16.5	17.5	22.4
Maximum TE altitude [m a.s.l.]	1660	1695	1662	1673
Mean TE altitude [m a.s.l.]	1530	1543	1447	1460
Minimum TE altitude [m a.s.l.]	1433	1435	1328	1329
Main forested area [ha]	86	101	136	166
Area of forest above the TE [ha]	6.5	7.4	5.1	12.0
Progressive TE length [km]	7.9	8.2	9.3	13.2
Stable TE length [km]	9.2	8.0	8.1	8.9
Regressive TE length [km]	0.29	0.28	0.13	0.32
TE line development ratio	4.2	3.7	3.4	3.0

the physiologically dependent range of climate suitable for tree vegetation. The course of the real border separating the forest from open spaces or areas occupied by dwarf mountain pine is far more diverse. The course was defined by computing the line development index. The recent shape of the TE is more complex in the Mengusovská Valley than in the Rybi Potok Valley (3.7 to 3.0, respectively). In 1949, the line development index of the main body of the forest in the Mengusovská Valley was 4.2 and after 60 years it reached 3.7. This indicates a simplification and corresponds with the shortening of the TE line, which takes place when a forest fills up the previously existing gaps, indentations, and other features. In the Rybi Potok Valley, the changes were the opposite. An increase in the number of polygons was noted and the course of the shape of the main body of the forest remained complex. In 1955, the line development index equaled to 3.4, and in 2009 it reached 3.0.

The changes of the spatial structure of the TE are connected with the changes of altitude where the ecotone appeared in the 20th and 21st century. In 1949, the timberline in the Mengusovská Valley ran at an average altitude of 1530 m a.s.l. (SD = 51). The lowest location of the TE was identified in the south-western part of the study area, where it descended to a height of 1433 m a.s.l. This particular descent was associated with an avalanche path on the western slope of Patria. The highest (1660 m a.s.l.) course of the TE was identified on the eastern slope of Predná Ostrva. In 2009, the average altitude of the TE increased slightly and reached the value of 1543 m a.s.l. (SD = 57). The lowest value of altitude of the TE changed by only 2 m. The place is located on the western slope

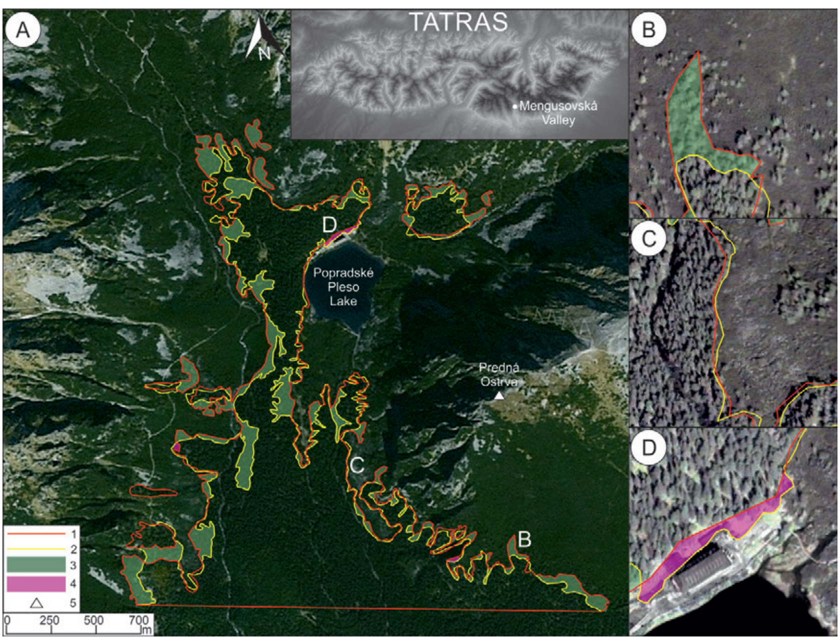

Figure 1. The course of the timberline in the Mengusovská Valley in 1949 and 2009
A – the recent and historical course of the timberline: (1) the timberline in 1949, (2) the timberline in 2009, (3) the polygons of the forested surface area increase, (4) the polygons of the forested surface area decrease; B – the example showing the progression of the timberline, here growth of the forest area is due to the increase in the crown cover density; C – the example of the stable timberline, the changes between the location of the timberline in 1949 and 2009, under 10 meters; D – the example of the regression of the timberline, here caused by human activity

of Patria but on another, more southerly situated avalanche path, which is entirely overgrown by dwarf mountain pine. In comparison with 1949, the maximum altitude at which the TE appeared in 2009 changed by 35 m and reached 1695 m a.s.l. The location itself did not change significantly, remaining the same slope 100 m to the SE. Sokołowski (1928) estimates that the maximum altitude of the spruce forest in the valley is 1550 m a.s.l., whereas Swiss pine forests reach up to 1600 m a.s.l. The average altitude at which the TE appeared in the Mengusovská Valley at the beginning of the 20th century, was 1515 m a.s.l.

In the Rybi Potok Valley, the changes of altitude at which the TE is located were similar. The average altitude at which the TE appeared in 1955 was 1447 m a.s.l. (SD = 62). The lowest point of the TE was located in the Żandarmeria chute, near the Rybi Potok Stream, at the northern side of the chute (1328 m a.s.l.). The descent was connected with avalanche activity in that chute. The TE reached its highest point near the Siedem Granatów Ridge (1662 m a.s.l.). It is a place where the highest parts of the forest are dominated by *Pinus cembra*. After 54 years, only two of the parameters changed. The average altitude of the appearance of the TE changed by 14 meters reaching a value of 1460 m a.s.l. with a similar variability (SD = 63). The altitude (1673 m a.s.l.) of the highest place where the TE runs changed comparably in the Mengusovská Valley. The point is situated in almost the same place (the Siedem Granatów Ridge) as the highest located forest in 1955. The lowest point of the TE is situated at almost the same altitude and place as in the middle of the 20th century.

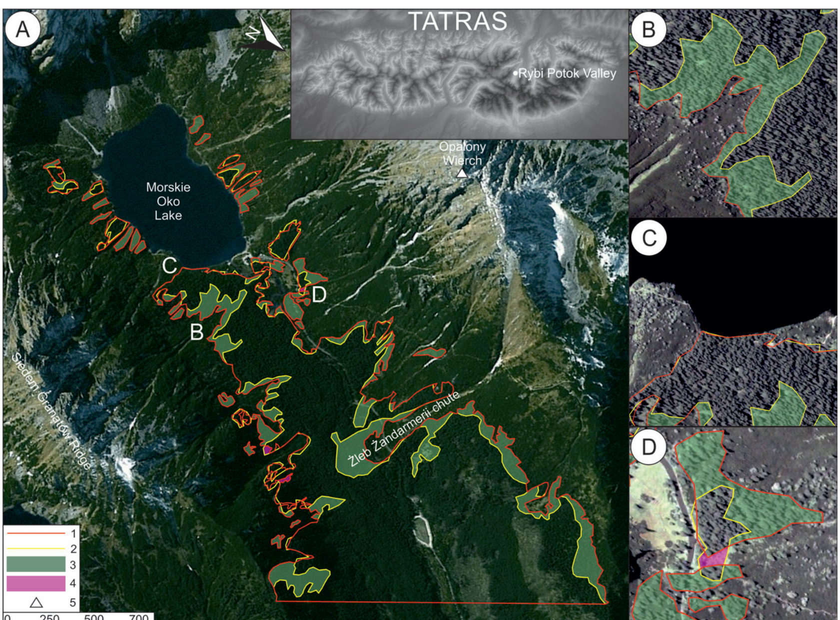

Figure 2. The course of the timberline in the Rybi Potok Valley in 1955 and 2009
A – the recent and historical course of the timberline: (1) the timberline in 1955, (2) the timberline in 2009, (3) the polygons of the forested surface area increase, (4) the polygons of the forested surface area decrease; B – an example showing the progression of the timberline, which here is due to reforestation of avalanche paths; C – an example of the stable timberline, the changes between the location of the timberline in 1955 and 2009, under 10 meters; D – an example of the regression of the timberline, here caused by snow avalanches

The particular changes in the course of the TE between 1949/1955 and 2009, varied in nature, scale, and spatial extent. The analysis of the local changes of the TE discerned 120 sections in the Mengusovská Valley and 159 sections in the Rybi Potok Valley. In the Mengusovská Valley, there are a majority of places where the TE is currently (as of 2009) located higher than in 1949 or where the forest increased its surface in a different way. The progressive TE represents 49.7% of the total length of the TE. At a similar length (48.6%), the TE did not change its position significantly. The descent of the TE is only present in 1.7% of its length. In the Rybi Potok Valley, the progressive TE takes up more space (59%), whereas a regressive TE is rare (1.4%).

The geographical characteristics of the occurring changes draw attention to the differences between the valleys. In the Mengusovská Valley, most (50%) of the TE where the increase of the forested surface area was recorded, is located on the slopes with a S and SW exposure. The predominant exposure of the slopes in the valley is also from the S and SW. This position guarantees more sunlight and encourages vegetation. It links the local changes of the TE directly to the climate warming. However, it is necessary to remember that some of the studied cases, especially those in the upper part of the valley, are connected with avalanche paths on the slopes of Popradský Hreben. The recent decrease of snow avalanche activity has allowed for the spontaneous reafforestation of the run-out zones. The exposure of places with a stable TE is similar to the general distribution of slope aspect in the valley (Tab. 1). A progressing TE is dominant throughout the Tatras (more than 60% of the length) (Guzik 2008) as well as in the western Czarnohora (Sitko & Troll 2008). This phenomenon, though, is not so common when considering the whole Carpathian Arc. For instance at Babia Góra Mt., changes of this type cover only 30% of the length of the timberline (Czajka et al. 2015).

In the Rybi Potok Valley, the major changes relating to the increase of forested surface area do not seem to be interlinked with slope aspect. On the slopes with E and SE exposure, 49% of such areas may be found. On the slopes with W and NW exposure, the percentage equals to 43%, which is comparable to the general exposure of the slopes in the studied part of the valley (Tab. 1). The stable TE is characterised by a similar correlation with the exposure of the slope.

The changes of the course of the TE induce the changes of forested surface area (Tab. 2). In comparison with the mid-20th century, this area in the Mengusovská Valley has increased by 156 ha. This increase is due to the formation of 62 polygons where the forested surface area has increased by a total of 166 ha, and of only 3 polygons where the forest decreased by a total of 10 ha. The most significant decrease of the forest is related to human activity and can be observed near a mountain shelter at Popradské Pleso Lake.

Most of the progressive changes in the valley constitute forest progression by a few or several acres with an average of 2.7 a (SD = 3.3). The largest growth of the forest area, up to 12 a, is associated with the reafforestation of the avalanche paths. This type of reafforestation is the most common type throughout the whole valley (Fig. 3). The forest progression in such areas is seen by the emergence of new trees in the lowest part or at the sides of a particular path. The increase in crown cover and the ability to meet the criteria for being a forest are two factors frequently found in equally percentages (39%). Such modifications result from slow, stable changes relating to the existence of favourable conditions during the studied period of time. For example, the forest has been freed from the economic pressure caused by pasturing and logging. The recent climate warming is another important factor improving the conditions for forest regeneration and growth.

The changes of the forest surface area in the Rybi Potok Valley reveal similar tendencies but the details differ. The expansion of the forested area (3.02 ha) clearly exceeds forest decrease (4.3 a). Forest spread is a result of the formation of 59 polygons with an average surface area of 8.1 a (SD = 5.1). Similarly

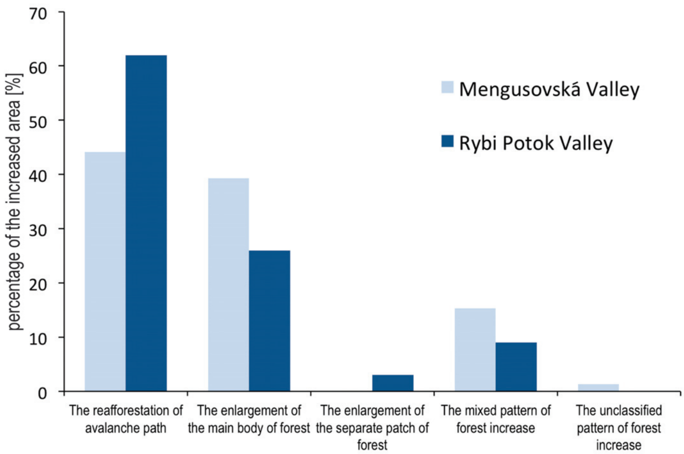

Figure 3. The character of the forest changes in the Mengusovská Valley and the Rybi Potok Valley between 1949/1955 and 2009

to the Mengusovská Valley, forest spread is associated with the reafforestation of avalanche paths (Fig. 3). However, the surface areas of the largest individual changes refer to both the reafforestation of avalanche paths and the increased crown cover, of tree stands that had already existed in 1955.

The high altitude variability at which the TE appeared in the middle of the 20th century was linked mainly with snow avalanches (Figs. 1 and 2). They caused the local lowering of the course of the TE (Fig. 4). The forest fragmentation in the timberline zone can also be related to snow avalanches. Furthermore, the effects of the avalanches are visible in the recent course of the TE. This information applies mainly to the Rybi Potok Valley where the avalanches that came directly down to the Morskie Oko Lake, fragmented the forest and contributed to the formation of 15 separate patches (as of 2009). All of them are connected with the tree stand which already existed in 1955 but did not have the full character of a forest. The reduction of avalanche activity in the analysed period is also reflected in the course of the TE in the main body of the forest. The decrease in the line development index is linked to the reafforestation of avalanche paths. In the Mengusovská Valley, the influence of avalanche paths on the course of the TE has a different character. The paths are far larger and reach the forest mainly by the runout zones. Avalanches lower the course of the TE without much impact on the fragmentation of the forest's surface area (Fig. 4). The reduction of avalanche activity led to the simplification of the course of the TE in that area. A situation with similar consequences occurred in the Western Tatras (the Kościeliska Valley), where between 1955 and 2004, as many as 70% of avalanche paths reaching the TE were shortened, narrowed or completely reforested by the upper montane forest belt (Czajka et al. 2012)

The reafforestation process of avalanche paths is constrained by the competition created by the *Pinus mugo* scrubs. The spruces and Swiss pines must compete with the scrubs for new areas (Guzik 2008; Šenfeldr et al. 2014). In many places, any further expansion of woody species seems to be effectively inhibited by the existence of this ecological barrier (Sokołowski 1928). An exception appears to be the S slopes of Ostrva where, despite the presence of a dense *Pinus mugo* cover, an increase in the density of the spruces led to a noticeable upwart shift of the TE, and presently new single trees grow above the TE.

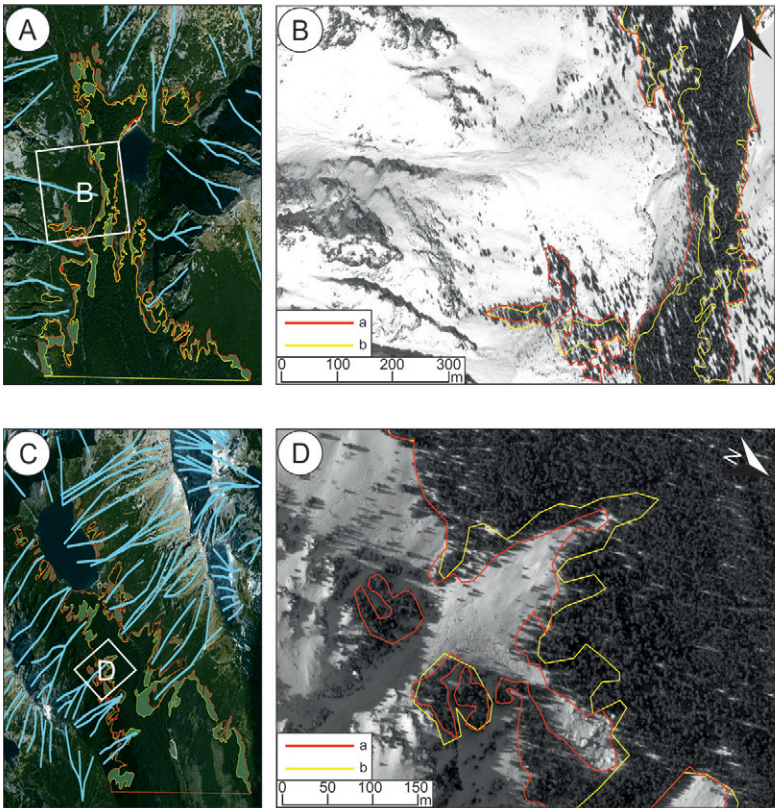

Figure 4. The examples of the influence of snow avalanches on the timberline ecotone
A – the snow avalanche paths in the Mengusovská Valley, B – the changes of the timberline between: (a) 1955 and (b) 2009; C – the snow avalanche paths in the Rybi Potok Valley, D – the changes of the timberline between: (a) 1955 and (b) 2009

Source: The maps of the snow avalanche paths were originally created for the Atlas of the Tatras (Žiak & Długosz 2015).

Conclusion

The overall picture of the changes in the course of the TE in the two valleys is similar. The predominant process is reafforestation: the increase of the elevation of the timberline (on average, by 10 m in the Mengusovská Valley and 15 m in the Rybi Potok Valley) and the closing up of free spaces.

The timberline has not changed its location over the past half-century and remains an important part of the ecotones in both valleys. In both valleys, the stable timberline constitutes almost a half of the total timberline length.

Deforestation dominates only a small percentage in both the Mengusovská Valley and the Rybi Potok Valley.

The progressive changes of the timberline are mainly related to a significant limitation of human economic activity and to climate warming.

The greatest enlargement of the forested area in both valleys is mainly because of inactive avalanche paths. The reduction of avalanche activity is a direct result of climate warming and the decrease of snow in winters.

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References

Bac-Moszaszwili M., Burchart J., Głazek J., Iwanow I., Jaroszewski W., Kotański Z., Lefeld J., Mastella L., Ziomkowski W., Roniewicz W., Skupiński A., Westwalewicz-Mogilska E., 1979. *Mapa geologiczna Tatr: 1:30,000*. Warszawa: Wydawnictwo Geologiczne.

Baker W.L., Honaker J.J., Weisberg P.J., 1995. *Using aerial photography and GIS, to map the forest-tundra ecotone in Rocky Mountain National Park, Colorado, for global change research*. Photogrammetric Engineering and Remote Sensing, vol. 61, no. 3, pp. 313-320.

Bohuš I., 2005. *Tatranské doliny w zrkadleni času*. Tatranská Lomnica: I&B.

Boltižiar M. 2007. *Štruktúra vysokohorskej krajiny Tatier (veľkomierkové mapovanie, analýza a hodnotenie zmien aplikáciou údajov diaľkového prieskumu Zeme)*. Nitra: Univerzita Konštantína Filozofa v Nitre.

Brockmann-Jerosch H., 1919. *Baumgrenze und Klimacharakter*. Beiträge zur geobotanischen Landesaufnahme, 6, Zürich: Rascher.

Brown D.G., 1994. *Predicting vegetation types at treeline using topography and biophysical disturbances*. Journal of Vegetation Sciences, vol. 5, no. 5, pp. 641-656.

Brown D.G., Cairns D.M., Malanson G.P., Walsh S.J., Butler D.R., 1994. *Remote sensing and GIS techniques for spatial and biophysical analyses of alpine treeline through process and empirical models* [in:] W.K. Michener, J.W. Brunt, S.G. Stafford (eds.), Environmental information management and analysis: Ecosystem to global scales, London: Taylor and Francis, pp. 453-481.

Chomicz K., Kňazovický L., 1974. *Lawiny* [in:] M. Konček (ed.), Klimat Tatr, Bratislava: Slovenská akademia vied, pp. 581-600.

Czajka B., Kaczka R.J., Guzik M., 2012. *Zmiany morfometrii szlaków lawinowych w Dolinie Kościeliskiej od utworzenia Tatrzańskiego Parku Narodowego* [in:] A. Łajczak (ed.), Antropopresja w wybranych strefach morfoklimatycznych – zapis zmian w rzeźbie i osadach, Prace Wydziału Nauk o Ziemi Uniwersytetu Śląskiego, 77, Sosnowiec: Wydział Nauk o Ziemi Uniwersytetu Śląskiego, pp. 126-135.

Czajka B., Łajczak A., Kaczka R.J., 2015. *The dynamics of the timberline ecotone on the asymmetric ridge of the Babia Góra Massif, Western Carpathians*. Geographia Polonica, vol. 88, no. 2, pp. 85-102.

de Quervain A., 1904. *Die hebung der atmosphärischen Isothermen in den Schweizer Alpen und ihre beziehung zu den Höhengrenzen.* Leipzig: Engelmann.

Gašpar M., 2002. *Tatry – staré pohladnice rozprávajú*. Poprad: Poprad Region.

Grace J., 1989. *Tree lines*. Philosophical Transactions of the Royal Society: Series B, 324, pp. 233-245.

GUGiK, 1999. *Zasady wykonywania prac fotolotniczych*: *Wytyczne techniczne K-2.7*. Warszawa: Główny Urząd Geodezji i Kartografii.

GUGiK, 2001. *Zasady wykonywania ortofotomap w skali 1:10,000*: *Wytyczne techniczne K-2.8*. Warszawa: Główny Urząd Geodezji i Kartografii.

Guzik M., 2008. *Analiza wpływu czynników naturalnych i antropogenicznych na kształtowanie się zasięgu lasu i kosodrzewiny w Tatrach*. Kraków: Uniwersytet Rolniczy im. Hugona Kołłątaja. Wydział Leśny. Katedra Botaniki Leśnej i Ochrony Przyrody [PhD thesis].

Guzik M., Bukowski M., 2009. *Wycofywanie pasterstwa z Tatrzańskiego Parku Narodowego*. Poster from a conference: Tatrzański Park Narodowy 1955-1977-2004. Długookresowe zmiany w przyrodzie i użytkowaniu obszaru TPN., 21-22 May 2009, Zakopane.

Harvan L., 1965. *Ako sa vyriešila pastva w TANAP*. Sborník prác o Tatranskom národnom parku, 8, Martin: Osveta, pp. 231-253.

Hess M., 1965. *Piętra klimatyczne w polskich Karpatach Zachodnich.* Zeszyty Naukowe Uniwersytetu Jagiellońskiego. Prace Instytutu Geograficznego, 33, Kraków: Uniwersytet Jagielloński

Holtmeier F.K., 2009. *Mountain timberline: Ecology, patchiness, and dynamics*. Advances in Global Change Research, 36, Dordrecht: Springer.

Hreško J., Boltižiar M., 2001. *Influences of the morphodynamic processes on the landscape structure in the high mountains (Tatry MTS area)*. Ekológia, vol. 20, suppl. 3, pp. 141-148.

Hreško J., Bugár G., Boltižiar M., Kohút F., 2008. *Dynamics of recent geomorphic processes in alpine zone of the Tatra Mts.* [in:] Geographia Polonica, vol. 81,no. 1, pp. 53-65.

Hutchinson G.E., 1957. *A treatise on limnology*. New York: J. Wiley,.

Jenness J., 2006. *Topographic Position Index (TPI) v. 1.2*. Flagstaff, AZ: Jenness Enterprises.

Jodłowski M., 2007. *Górna granica kosodrzewiny w Tatrach, na Babiej Górze iw Karkonoszach: struktura i dynamika ekotonu*. Kraków: Instytut Geografii i Gospodarki Przestrzennej Uniwersytetu Jagiellońskiego.

Kapusta J., Stankoviansky M., Boltižiar M., 2010. *Changes in activity and geomorphic effectiveness of debris flows in the High Tatra Mts. within the last six decades (on the example of the Velická Dolina and Dolina Zeleného Plesa Valleys.* Studia Geomorphologica Carpatho-Balkanica, 44, pp. 5-35.

Klimaszewski M., 1988. *Rzeźba Tatr Polskich*. Warszawa: Państwowe Wydawnictwo Naukowe.

Kłapowa M., 1969. *Obserwacje lawin śnieżnych w Tatrach*. Wierchy, 38, pp. 137-153.

Kłapowa M., 1976. *Mapa zagrożenia lawinowego w Tatrach – Tatry Zachodnie. Wynik kartowania lawin śnieżnych zimą 1969/1970.* Map at a scale 1:10,000.

Kotarba A., 1995. Rapid mass wasting over the last 500 years in the High Tatra Mountains. Questionaes Geographicae, spec. issue, vol. 4, pp. 177-183.

Kotarba A., Kaszowski L., Krzemień K., 1987. *High-mountain denudational system of the Polish Tatra Mountains*. Geographical Studies Special Issue, 3, Wrocław-Warszawa: Ossolineum, Instytut Geografii i Przestrzennego Zagospodarowania PAN.

Kotarba A., Rączkowska Z., Długosz M., Boltižiar M., 2013. *Recent debris flows in the Tatra Mountains* [in:] D. Loczy (ed.), *Geomorphological impacts of extreme weather*: *Case studies from Central and Eastern Europe*, Dordrecht-New York: Springer, pp. 221-236.

Kotarba A., Starkel L., 1972. *Holocen morphogenetic altitudinal zones in the Carpathians*. Studia Geomorphologica Carpatho-Balcanica, 6, pp. 21-35.

Kozłowska A., 2008. *Strefy przejścia między układami roślinnymi – analiza wielkoskalowa na przykładzie roślinności górskiej*. Prace Geograficzne, 215, Warszawa: Instytut Geografii i Przestrzennego Zagospodarowania PAN.

Krzemień K., 1988. *The dynamics of debris flows in the upper part of the Starorobociańska Valley (Western Tatra Mts.)*. Studia Geomorphologica Carpatho-Balcanica, 22, pp. 123-144.

Lukniš M., 1973. *Reliéf Vysokých Tatier a ich predpolia*. Bratislava: Vydavatelstvo Slovenskej akadémie vied.

Midriak R., 1977. *Antropogénne vplyvy na vegetáciu a pôdu vo vysokých pohoriach Západných Karpýt*. Zborník Lesníckeho, drevárskeho a polovníckeho múzea, 9, Zvolen: Lesnícke drevárske a poľovnícke múzeum v Antole, pp. 141-182.

Mirek Z., 1996. *Antropogeniczne zagrożenia i przekształcenia środowiska przyrodniczego* [in:] Z. Mirek (ed.), Przyroda Tatrzańskiego Parku Narodowego. Kraków-Zakopane: Tatrzański Park Narodowy, pp. 595-617

Motta R. Nola P., 2001. *Growth trends and dynamics in sub-alpine forest stands in the Varaita Valley (Piedmont, Italy) and their relationship with human activities and global change*. Journal of Vegetation Science, vol. 12, no. 2, pp. 219-230.

Nemčok J. (ed.), 1994. *Geologická mapa Tatier 1:50,000*. Bratislava: Geologický ústav Dionýza Štúra.

Plesnik P., 1973. *La Limite Supérieure de la Forêt dans les Hautes Tatras*. Arctic, Antarctic and Alpine Research vol. 5, no. 3, pp. 37-44.

Pociask-Karteczka Z. (ed.), 2006. *Zlewnia: Właściwości i procesy*. Kraków: Wydawnictwo Uniwersytetu Jagiellońskiego.

Rączkowska Z., 2006. *Recent geomorphic hazards in the Tatra Mountaains*. Studia Geomorphologica Carpatho-Balcanica, 40, pp. 45-60.

Rączkowska Z., 2007. *Współczesna rzeźba peryglacjalna wysokich gór.* Prace Geograficzne, 212, Warszawa: Instytut Geografii i Przestrzennego Zagospodarowania PAN.

Rączkowska Z., 2008. *Współczesna ewolucja rzeźby Tatr* [in:] Starkel L., Kostrzewski A., Kotarba A., Krzemień K., (eds.), Współczesne przemiany rzeźby Polski, Kraków: Instytut Geografii i Gospodarki Przestrzennej Uniwersytetu Jagiellońskiego, pp. 36-56.

Rączkowska Z., Łajczak A., Margielewski W., Święchowicz J., 2012. *Recent landform evolution in the Polish Carpathians* [in:] D. Lóczy, M. Stankoviansky, A. Kotarba, (eds.), Recent landform evolution: The Carpatho-Balkan-Dinaric Region. Dordrecht-New York: Springer, pp. 47-101.

Sitko I., Troll M., 2008. *Timberline changes in relation to summer farming in the Western Chornohora (Ukrainian Carpathians).* Mountain Research and Development, vol. 28, no. 3, pp. 263-271.

Slaymaker O., Embleton-Hamman Ch., 2009. *Mountains* [in:] O. Slaymaker, T. Spencer Ch. Embleton-Hamman (eds.), Geomorphology and global environmental changes, Cambridge: Cambridge University Press, pp. 37-70.

Sokołowski M., 1928. *O górnej granicy lasu w Tatrach*. Kraków: Zakłady Kórnickie, pp. 155.

Šenfeldr M., Treml V., Maděra P., Volařík D., 2014. *Effects of prostrate dwarf pine on norway spruce clonal groups in the treeline ecotone of the Hrubý Jeseník Mountains, Czech Republic*. Arctic, Antarctic, and Alpine Research, vol. 46, no. 2, pp. 430-440.

Tollner H., 1949. *Der Einfluß großer Massenerhebungen auf die Lufttemperatur und die Ursachen der Hebung der Vegetationsgrenzen in den inneren Ostalpen*. Archiv für Meteorologie, Geophysik und Bioklimatologie: Serie B, vol. 1, no. 3-4, pp. 347-372.

Troll C., 1973. *The upper timberline in different climatic zones*. Arctic and Alpine Research, vol. 5, pp. 3-18.

Walsh S.J., Butler D.R., Allen T.R., Malanson G.P., 1994. *Influence of snow patterns and snow avalanches on the alpine treeline ecotone*. Journal of Vegetation Sciences, vol. 5, no. 5, pp. 641-656.

Weisberg P.J., Shandra O., Becker M.E., 2013. *Landscape influences on recent timberline shifts in the Carpathian Mountains: Abiotic influences modulate effects of land-use change*. Arctic, Antarctic, and Alpine Researche, vol. 45, no. 3, pp. 404-414.

Wężyk P., Guzik M., 2004. *The use of "Photogrammetry-GIS" (P-GIS) for the analysis of changes in the Tatra Mountains' natural environment* [in:] W. Widacki, A. Bytnerowicz, A. Riebau (eds.), A message from the Tatra: Geographical Information Systems and Remote Sensing in Mountain Environmental Research. Kraków-Riverside: Jagiellonian University Press, USDA Forest Service. pp. 31-46.

Žiak M., Długosz M., 2015. *Szlaki lawinowe*. 1:100,000. [in:] Atlas Tatr (in print).

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