GEOGRAPHICAL CONTROLS ON THE COURSE OF THE UPPER MOUNTAIN PINE (*Pinus mugo*) LIMIT IN THE TATRA MTS

MIŁOSZ JODŁOWSKI

Institute of Geography and Spatial Management, Jagiellonian University, Gronostajova 7, 30-387 Cracow, Poland, e-mail: m.jodlosz@geo.uj.edu.pl

Abstract

Jodłowski M.: Geographical controls on the course of the upper mountain pine (*Pinus mugo*) limit in the Tatra Mts. Ekológia (Bratislava), Vol. 25, Supplement 1/2006, p. 105–114.

The pattern of forest – alpine tundra ecotone has been investigated in six valleys in Tatra Mts: the Kezmarska, the Batizovska, the Velicka, the Ziarska, the Mała Łąka and the Bielovodská dolina valleys. They have been chosen on the basis of their predominant aspect, variability of geology and relief, and either peripheral or central location within the massif. Approximately 63.5 km of krummholz line were surveyed. In the study area krummholz line is located at 1365–1940 m a.s.l. and its average altitude ranges from 1619 to 1764 m a.s.l. The impact of factors controlling the krummholz line – i.e. climate, geology, relief as well as the human impact – has been assessed. Climatic factors restrain krummholz forms from growing above defined altitude, but do not directly control the boundary of close dwarf-pine thickets. Geomorphic processes i.e. avalanches and debris flows as well as orography and landforms are the critical controls on the contemporary pattern of the krummholz line.

Key words: mountain pine, subalpine belt, krumholz-line, Tatra Mts

Introduction

In the mountains of Central Europe – e.g. the Carpathians, the Eastern Alps and the Giant Mountains - the separate physicogeographical vertical zone with dwarf-pine (*Pinus mugo*) thickets occurs. This zone is named *Kampfzone* or *Kampfguertel* in the Alps (Holtmeier, 1972; Troll, 1973a; Körner, 1998). It plays a significant role in the functioning of the natural environment. Mountain pine protects the soil, stabilises the snow cover thus hampering the release of avalanches, and provides habitat for many species of flora and fauna.

In this paper upper dwarf-pine limit is treated as part of the forest – alpine tundra ecotone (Fig. 1) and constitutes the equivalent of krummholz-line cited in alpine literature (Löve,

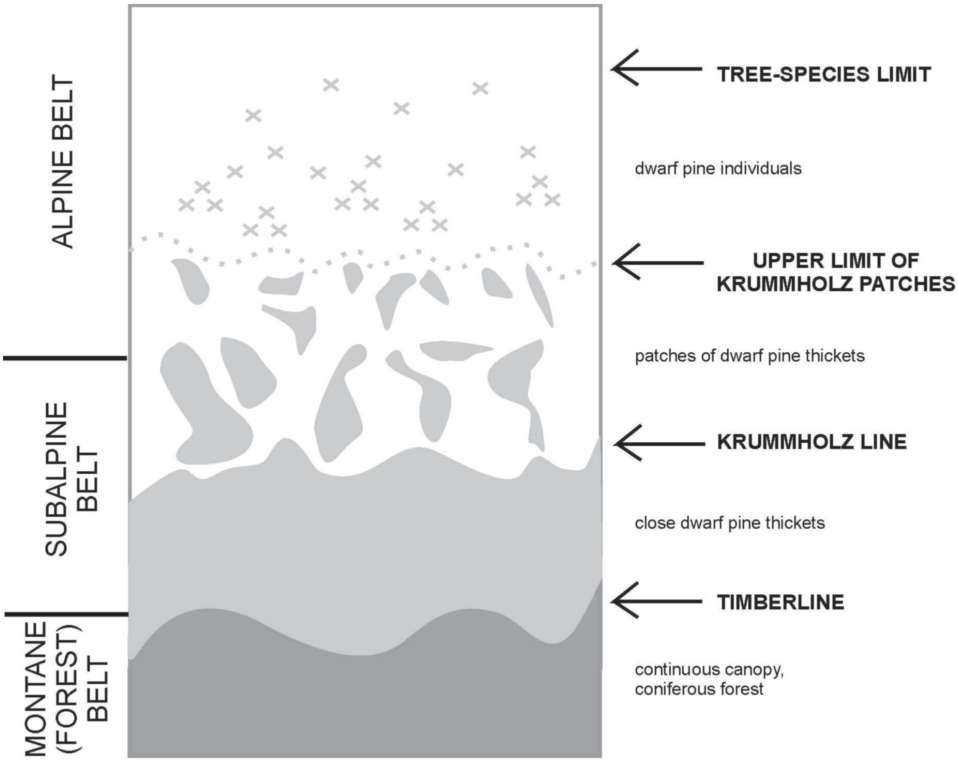


Fig. 1. Forest – alpine tundra ecotone in the Tatra Mts.

1970; Holtmeier, 1981; Slatyer, Noble, 1992). In Polish physicogeogarphical literature it is identified with the upper limit of subalpine belt (Piękoś-Mirkowa, Mirek, 1996; Balon, 2000). This boundary is one of the most important and at the same time insufficiently investigated landscape boundaries in the mountains.

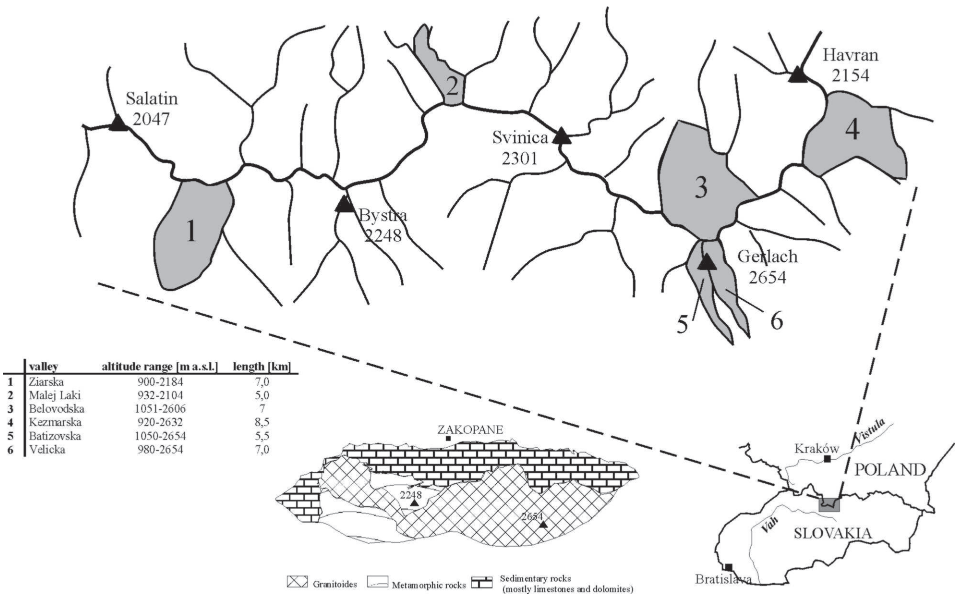
Vast majority of publications refers to the timberline understood as the upper limit of continuous canopy forest (Fig. 1). Factors influencing its course at global as well as local scale were studied by botanists, plant ecologists (Wardle, 1971, 1974; Tranquillini, 1979; Stevens, Fox, 1991; Körner, 1998; Jobbagy, Jackson, 2000) and forestrians (Arno, 1984) as well as physical geographers (Troll, 1973a; Brown, 1994; Butler, Walsh, 1994). The conclusions presented in these works also refer to the krummholz line. The problem of the upper limit of dwarf pine was also brought up in geoecological and landscape-ecology research on vertical zonality in natural environment (Holtmeier, 1973; Troll, 1973b; Kotarba, 1987; Balon, 1992). There are few publications directly concerning the krummholz line (Daly, 1984; Seko, 1979, 1984).

In the Tatra Mts the problem of timberline was discussed in monographs by Sokołowski (1928) and Plesnik (1971) as well as in several studies on the influence of particular controls on the course of the boundary (e.g. Kňazovický, 1970; Krzemień et al., 1995; Plesnik, 1978). Stability of the upper limit of dwarf pine was investigated by Balon (2003).

The aim of this study is to assess the impact of environmental features and physicogeographic processes on the altitude, course and pattern of krummholz line in the Tatra Mountains. Geology, climate features, landforms and geomorphic processes are considered to be the main factors affecting this boundary. Human impact is also of great importance. Another aim is to re-assess the structure and characteristics of the so-called dispersed dwarf-pine zone, mentioned briefly by Kotula (1889–1890) and not addressed since. The results of the author's investigation conducted on the occurrence, continuity and typical features of dispersed dwarf-pine zone are presented in this paper.

Methods and characteristics of the study area

The study area comprises six valleys in the Tatra Mts, on the Slovak as well as the Polish side of the state border. These are the Kezmarska, the Belovodska, the Batizovska and the Velicka dolina valleys in the High Tatra Mts as well as the Ziarska and the Mała Łąka valleys in the Western Tatra Mts. The valleys have been chosen for the investigation on the basis of their predominant aspect, variability of geology and relief, and either peripheral or central location within the massif. In three valleys i.e. the Kezmarska, the Mała Łąka and the Ziarska dolina valleys, the krummholz line has been significantly lowered by human activity. In the remaining 3 valleys human impact was comparatively smaller (Plesnik, 1971, 1978). Location of the study area, geology and basic morphometric characteristics of the studied valleys are presented in Fig. 2.



	valley	altitude range [m a.s.l.]	length [km]
1	Ziarska	900-2184	7,0
2	Malej Laki	932-2104	5,0
3	Belovodska	1051-2606	7
4	Kezmarska	920-2632	8,5
5	Batizovska	1050-2654	5,5
6	Velicka	980-2654	7,0

Fig. 2. Location of the study area. Geology.

The fieldwork involved mapping the upper boundary of close dwarf pine thickets and the patches of dispersed dwarf pine was conducted in four valleys (leaving out the Mała Łąka and the Kezmarska dolina valleys, where the course of krummholz line is not linear as a result of intense anthropopression. Mapping was carried out in 1:10 000 scale. Data derived from aerial photographs were verified in the field. Full photographic documentation of the ecotone was made.

Data concerning environmental features were collected directly in the field. They were also derived from the following cartographic materials: 1:10 000 topographic maps of Slovakia, geological map of the Tatra Mts in 1:50 000 scale (Nemčok, 1995), morphological map of the High Tatra Mts in 1:50 000 scale (Lukniš, 1973) and digital maps of slope aspect and gradient computed on the basis of digital elevation model (DEM). The variability of the mean annual temperature was calculated using linear regression equations in which temperature is dependent on altitude, aspect and relief (Hess et al., 1975). DEM was created by digitising 1:25 000 topographic maps in ArcInfo and MapInfo.

The occurrence of geomorphic processes lowering the krummholz line such as avalanches, debris flows and rockfalls as well as landforms corresponding to the boundary of close dwarf-pine thickets and patches of dwarf pine were mapped in the field and marked in earlier elaborated survey form.

Results

Pattern of the krummholz line

Approximately 63.5 km of krummholz line (or timberline, if there is a lack of close mountain pine thickets) were surveyed, out of which 32 km in the Belovodska dolina valleys, 23.5 km in the Ziarska dolina valley and 8 km in the Batizovska and the Velicka dolina valleys. In the study area krummholz line is located at 1365–1940 m a.s.l. and its average altitude ranges from 1619 to 1764 m a.s.l. (Table 1). Thus, the lowest altitudes of krummholz line are significantly lower than climate driven timberline. Vertically, forest – alpine ecotone stretches for approximately 350–400 metres in the Batizovska and the Velicka dolina valleys and approximately. 500–600 metres in the Belovodska dolina valley. The highest sites of dwarf pine individuals can be found at 2100–2150 m a.s.l (Fig. 3).

In the Tatra Mts, three landscape boundaries could be distinguished in the forest - alpine tundra ecotone above the timberline. These are: krummholz line, upper limit of krummholz patches and tree-species limit (Fig. 1). At some reaches, close dwarf pine thickets zone is decreased to some dozens metres and on the eastern slopes of Mlynar massif there is a 4.5 km break in the course of krummholz line.

Factors controlling the krummholz line

Climate

The krummholz line is identified with the upper limit of very cool climatic belt, which corresponds to 0°C isotherm (Hess, 1965, 1974). This isotherm runs at about 1850 m a.s.l. on the northern slopes and at about 2050 m a.s.l. on the southern slopes i.e. considerably higher than the krummholz line. Only when linear regression equations in which mean annual air temperature is dependent on relief variability (concave and convex forms) were

T a b l e 1. Landforms and geomorphic processes controlling the krummholz line altitude

Valley	Krummholz line				Geomorphic processes lowering the krummholz line						Dissection of the zone down to the timberline	
					avalanches		debris flows		rock falls		number	average altitude
	total length	average altitude	maximum altitude	minimum altitude	number	average altitude	number	average altitude	number	average altitude		
Belovodska dolina	26980	1618.9	1870	1410	14	1573.93	–	–	–	–	3	1455
Batizovska and Velicka dolina	8060	1764.1	1940	1650	5	1690	1	1680	–	–	–	–
Zarska dolina	22920	1691.3	1900	1365	32	1531.41	13	1488,5	1	1650	14	1480

	local maximum of the krummholz line			landforms									
				valley bottoms		slopes		watershed ridges		crests		gullies	
	total number	average altitude	average uprising of the krummholz line [m]	number	average altitude	number	average altitude	number	average altitude	number	average altitude	number	average altitude
Belovodska dolina	26	1798.3	+106.97	1	1830	10	1774	4	1871	9	1812.2	2	1695
Batizovska and Velicka dolina	14	1832.9	+68.76	1	1850	3	1878.3	4	1910	6	1755.8	–	–
Zarska dolina	50	1683.2	+64.3	–	–	8	1688.1	2	1800	40	1676.4	–	–

	local minimum of the krummholz line			landforms									
				valley bottoms		slopes		watershed ridges		crests		gullies	
	total number	average altitude	average lowering of the krummholz line [m]	number	average altitude	number	average altitude	number	average altitude	number	average altitude	number	average altitude
Belovodska dolina	25	1612.8	–78.5	3	1621.67	7	1672.9	1	1795	1	1800	13	1550
Batizovska and Velicka dolina	14	1722.5	–41.6	2	1720	7	1746.4	–	–	–	–	5	1690
Zarska dolina	52	1550.88	–68.02	8	1528.9	6	1651	–	–	2	1600	36	1541.25

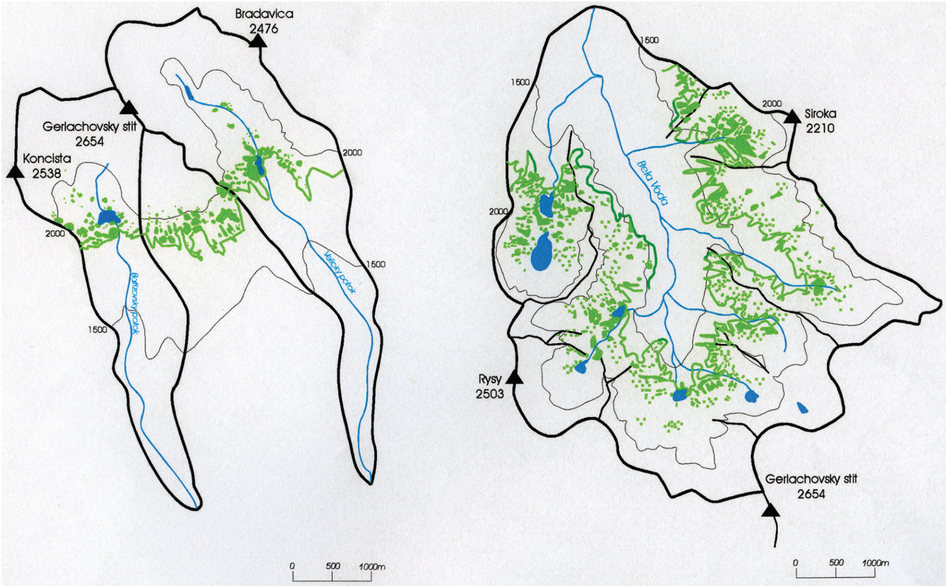


Fig. 3. Pattern of the krummholz line in the Belovodska, Batizovska and Velicka dolina valleys.
Legend: 1 – catchment border, 2 – contour lines, 3 – main peaks, 4 – krummholz line, 5 – patches of dwarf pine.

taken into consideration, the interdependence between temperature and altitude of the upper limit of krummholz line in the valleys located north from the main Tatra ridge could be identified. The theoretical altitude of 0°C isotherm for the concave and convex forms is respectively 1863 m a.s.l. and 1634 m a.s.l. The average altitude of krummholz line corresponds well with the altitude of 0°C isotherm given by Kotarba (1987).

The microclimatic factors are of great significance in controlling the pattern of krummholz line. Insolation, thickness of the snow cover as well as humidity are frequently mentioned to be the most important (Bukovčan, 1953; Holtmeier, 1981; Daly, 1984; Seko, 1984; Körner, 1998). Dwarf pine avoids moister and shaded locations, with longer snow cover duration. The field observations confirm this hypothesis but further research need to be conducted.

Geology

In the Tatra Mts krummholz line runs mainly on the surface composed of crystalline rocks. Reaches of krummholz line on sedimentary rocks (limestone and dolomites) occur in some valleys in the Western Tatra Mts (the Jalovska, the Kościeliska and the Mała Łąka dolina valleys), the High Tatra Mts (the Javorova and the Belovodska dolina valleys) but mainly in the Belianske Tatra Mts. However, in these areas the krummholz line has been significantly lowered by human activity i.e. obtaining new pastures on relatively fertile soils as well as cutting down for oil and charcoal production (Plesnik, 1978). The average altitude of krummholz line on sedimentary rocks in the Belovodska dolina valley is 1682 m a.s.l., i.e. about 70 metres higher than the average for the whole valley. Higher average altitude of timberline on carbonate rocks is also given by Krzemień et al. (1995). Limited length of such reaches (ca 2 km) does not allow to unequivocally state the dependence of krummholz line on geology.

Relief

Geomorphic factors are the most important group of factors controlling contemporary pattern of krummholz line. Morphometry, landforms and geomorphic processes should be analysed separately.

Slope aspect and gradient determine the insolation values and as such they modify the pattern of climate driven krummholz line. Krummholz-line altitude on slopes with particular aspects is shown in Fig. 4. The most distinct relationship between the aspect and krummholz-line altitude was identified in the Batizovska and the Velicka dolina valleys. Krummholz line runs highest on the slopes with southern aspect (average altitude – 1829 m a.s.l.). In the Belovodska dolina valley highest krummholz-line altitudes can be observed on south-eastern and eastern slopes. However, considerable relief dissection in the Belovodska dolina valley causes that correlation between aspect and krummholz-line altitude is not a strong one. The krummholz line on the slopes with southern aspect has been lowered by human activity. As a result, it now has the lowest elevation on the surfaces with the favourable slope aspect. In the Ziarska dolina valley anthro-

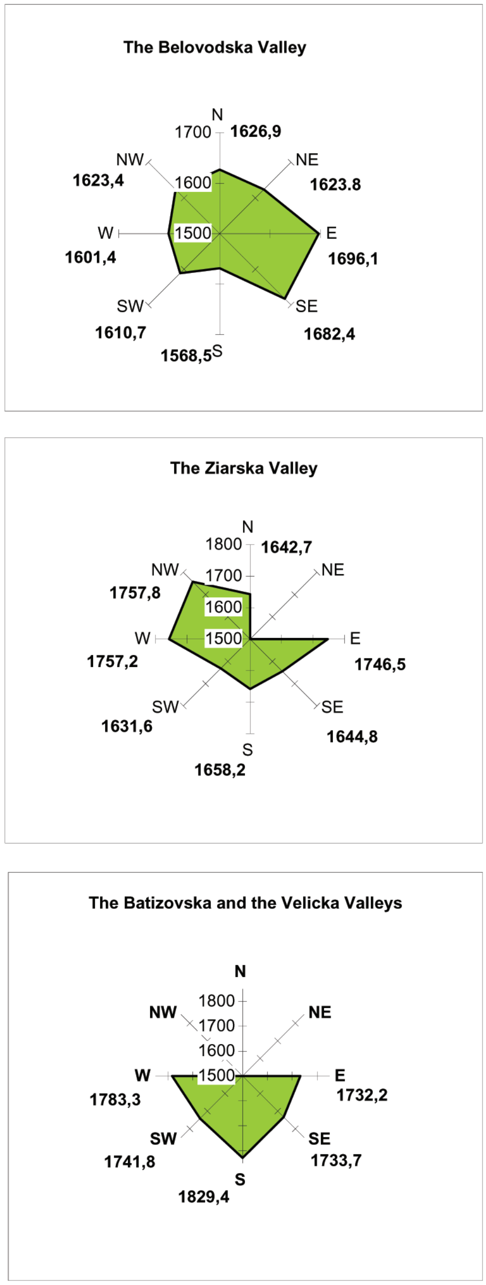


Fig. 4. Relationship between krummholz-line altitude and slope aspect.

pogenic lowering of krummholz line was particularly significant and contemporary krummholz line has the highest altitude on the slopes with the least favourable aspects.

Slope gradient does not constitute a restraint for krummholz. Dwarf pine occurs even on the steep slopes with gradient exceeding 45°. However, in the vicinity of potential, i.e. climate driven krummholz line the gradient may be an additional factor likely to lower its course. Some krummholz-line reaches run along slope breaks (e.g. at the foot of rock faces and rocky slopes).

In order to present the influence of geomorphic processes and landforms on the course of the krummholz line in the study area, 90 local minima and 90 maxima of the krummholz line were analysed (Table 1). There is considerable influence of orography on krummholz line. The vast majority of local minima corresponds to convex forms i.e. watershed ridges and crests, while minima fall on concave forms: valley bottoms, chutes and gullies. The phenomenon of timberline-lowering in the valley bottoms mentioned in the literature (Sokołowski, 1928; Plesnik, 1971; Holtmeier, 1973; Brown, 1994) is also valid in the case of krummholz line. Krummholz line in the valley bottoms runs from 40 (the Batizovska and the Velicka dolina valleys) to 90 (the Belovodska dolina valley) metres lower than its average altitude. Absolute maxima of krummholz-line altitude were observed on watershed ridges, where krummholz line runs from 120 to 150 metres higher than the average. Krummholz-line occurrence is characteristic on the edges of hanging valleys (Fig. 3).

Avalanches and debris flows are considered the major geomorphic processes modifying the pattern of timberline (Erschbammer, 1989; Patten, Knight, 1995; Butler, Walsh, 1994; Krzemień et al., 1995). In the study area, over 50 per cent of local krummholz-line minima correspond to avalanche paths. The largest avalanches occur on the slopes of Rosocha and Baranec in the Ziarska dolina valley (Kňazovický, 1970) as well as on the eastern slopes of the Belovodska valley. Here the krummholz line is most significantly lowered with absolute minima of1365 m and 1410 m a.s.l. (Table 1). In 17 cases avalanche paths run across the entire zone of close pine-thickets and reach timberline (see also Hreško, Boltižiar, 2001).

Dispersed dwarf-pine zone

Dispersed dwarf pine-zone (mentioned by Kotula in 1889–1890) occurs commonly in the Tatra Mts, however its width, altitude and pattern varies depending on the valley (Fig. 3). Dispersed dwarf-pine patches correspond to the locations with more favourable habitats, i.e. convex forms, sites with higher insolation values, lower gradient and with continuous soil cover. They are also present on rocky ledges within rock faces. Field observations imply that the size of dwarf-pine patches decreases with altitude while canopy within the patches does not change. Canopy seems to be dependent on the type of slope covers and is characterised by considerably lower density on not stabilised rocky-regolith and regolith slopes.

Human impact is one of the most important factors influencing the pattern of this zone. Human activity has caused a decrease or total disappearance of the zone. At present, a reverse process is being observed: reconstruction of dwarf pine causes krummholz line to gradually increase in altitude. In the Ziarska dolina valley and in the adjacent Tarnovecka dolina valley, dwarf-pine patches introduced by man are characterised by relatively limited canopy: 20–50% of the patch area.

Discussion and conclusions

According to the vast majority of authors, the upper limit of subalpine belt in the Tatra Mountains, understood as an equivalent of the upper boundary of dwarf-pine thickets, reaches an altitude of 1800–1850 m a.s.l. (Pawłowski, 1959; Piękoś-Mirkowa, Mirek, 1996). The krummholz line i.e. the upper boundary of close dwarf-pine thickets, runs about 150-200 metres lower. Thus, one might assume that the upper limit of subalpine belt follows the upper limit of krummholz patches. However, this boundary, as a climate-driven one, is not sharp and precise delineation of its course is problematic. The patch-size criterion does not seem to be appropriate.

Climatic factors restrain krummholz forms from growing above defined altitude, but do not control the boundary of close dwarf-pine thickets directly. The critical controls on the contemporary pattern of the krummholz line are geomorphic processes, orography and landforms.

In the studied valleys, microclimate, dynamics of geomorphic processes and properties of soil cover are the most significant factors likely to control the krummholz line in toposcale. Further studies are needed to precisely determine the impact of these factors.

Translated by the author

References

Arno, S., 1984: Timberline. Mountain and Arctic Forest Frontiers. The Mountaineers, Washington, 302 pp.

Balon, J., 1991: Vertical zonality in natural environment of the Tatra Mts (in Polish). Czas. Geogr., *62*, 4, p. 283–299.

Balon, J., 2000: Physico-geographic vertical zones in the Polish Tatra Mts (in Polish). Prace Geograficzne UJ, *105,* p. 211–233.

Balon, J., 2003: The upper dwarf-pine zone limt as the indicator of environment stability (in Polish). In print.

Brown, D.G., 1994: Comparison of vegetation-topography relationships at the alpine treeline ecotone. Physical Geography, *15*, 2, p. 125–145.

Bukovčan, V., 1953: Dwarf Mountain Pine (in Slovak). Bratislava.

Butler, D.R., Walsh, S.J., 1994: Site characteristics of debris flows and their relationship to alpine treeline. Physical Geography, *15*, 2, p. 181–199.

Daly, Ch., 1984: Snow distribution patterns in the alpine krummholz zone. Progress in Physical Geography, *8*, 1, p. 157–175.

Erschbamer, B., 1989: Vegetation on avalanche paths in the Alps. Vegetatio, *80*, p. 139–146.

Hess, M., 1965: Climatic Vertical Zones in the Polish Western Carpathians (in Polish). Prace Geograficzne, *11*, 258 pp.

Hess, M., 1974: Climatic vertical zones of the Tatra Mountains (in Polish). Czasopismo Geograficzne, *45*, 1, p. 75–95.

Hess, M., Niedźwiedź, T., Obrębska-Starklowa, B.L., 1975: Contribution to the methods of construction of climatic maps of various scales for mountainous and upland territories (in Polish). Prace Geograficzne UJ, 41, p. 7–35.

Holtmeier, F.-K., 1972: The influence of animal and man on the alpine timber-line. In Troll, C. (ed.): Geoecology of the high-mountain regions of Eurasia. Proceedings of the symposium of the International Geographical Union Commission on High-Altitude Geoecology, November, 20-22, 1969 at Mainz, Franz Steiner Verlag, Wiesbaden, p. 93–97.

Holtmeier, F.-K., 1973: Geoecological aspects of timberlines in Northern and Central Europe. Arct. Alp. Res., *5*, 3, 2, p. A45–A54.

Holtmeier, F.-K., 1981: What does the term 'krummholz' really mean? Observations with special reference to the Alps and the Colorado Front Range. Mount. Res. Dev., *1*, 3–4, p. 253–260.

Hreško, J., Boltižiar, M., 2001: Influences of the morphodynamic processes on the landscape structure in the high mountains (Tatry Mts area). Ekológia (Bratislava), *20*, Supplement 3/2001, p. 141–149.

Jobbagy, E.G., Jackson, R.B., 2000: Global controls of forest line elevation in the northern and southern hemispheres. Global Ecology & Biogeography, *9*, p. 253–268.

Körner, Ch., 1998: A re-assessment of high elevation treeline positions and their explanation. Oecologia, *115*, p. 445–459.

Kňazovický, L., 1970: The Western Tatra Mountains (in Slovak). Vydavatel'stvo SAV, Bratislava, 216 pp.

Kotarba, A., 1987: Geoecological belts. In High mountain denudational system of the Polish Tatra Mountains. PAN IGiPZ, Geographical Studies, Special Issue, *3*, p. 38–44.

Kotula, B., 1889-1890: Distribution of vascular plants in the Tatra Mts (in Polish). Akademia Umiejętności, Kraków.

Krzemień, K., Libelt, P., Mączka, T., 1995: Geomorphological conditions of the timberline in the Western Tatra Mountains. Prace Geograficzne UJ, *98*, p. 153–170.

Löve, D., 1970: Subarctic and subalpine: where and what?. Arct. Alp. Res., *2* ,1, p. 63–73.

Luknia, M., 1973: Relief of the High Tatra Mountains (in Slovak). Veda, SAV, Bratislava, 375 pp.

Nemčok, J., 1995: Geological map of the Tatra Mts, 1:50 000 scale (in Slovak). Geologický Ústav Dionýza Štúra, Bratislava.

Patten, R.S., Knight, D.H., 1995: Snow Avalanches and Vegetation Pattern in Cascade Canyon. Grand Teton National Park, Wyoming, U.S.A., Arct. Alp. Res., *26*, 1, p. 35–41.

Pawłowski, B., 1959: Vegetation of the Polish mountains (in Polish). In Vegetation of Poland. PWN, Warszawa.

Piękoś-Mirkowa, H., Mirek, Z., 1996: Plant communities (in Polish). In Mirek, Z. (ed.): Nature of the Tatra National Park. Kraków - Zakopane, p. 237–274.

Plesnik, P., 1971: The Timberline in the High and Belianskie Tatra Mts (in Slovak). Vydavatel'stvo SAV, Bratislava, 238 pp.

Plesnik, P., 1978: Man's influence on the timberline in the West Carpathian Mountains, Czechoslovakia. Arct. Alp. Res., *10*, 2, p. 491–504.

Seko, L., 1979: On the synmorphology of the upper dwarf-pine zone in the Nizke Tatra Mts (in Slovak). Acta Facultatis Rerum Naturalium Universitatis Comenianae, Geographica, *17*, p. 137–147.

Seko, L., 1984: About Spatial Differentiation of Crook Growth in Dumbier Group of the Low Tatras (in Slovak). Acta Facultatis Rerum Naturalium Universitatis Comenianae, Geographica, *23*, p. 121–141.

Slatyer, R.O., Noble, I.R., 1992: Dynamics of Montane Treelines. In Hansen, A.J., di Castri, F. (red.): Landscape Boundaries. Consequences for Biotic Diversity and Ecological Flows. Ecological Studies, *92*, p. 346–359.

Sokołowski, M., 1928: About timberline in the Tatra Mountains (in Polish). Wyd.Fund."Zaklady Kórnickie",1, Kraków.

Stevens, G.C., Fox, J.F., 1991: The causes of treeline. Ann. Rev. Ecol. Syst., *22*, p. 177–191.

Tranquillini, W., 1979: Physiological Ecology of the Alpine Timberline. Tree Existence at High Altitudes with Special Reference to the European Alps. Ecological Studies, *31*, 137 pp.

Troll, C., 1973a: The upper timberlines in different climatic zones. Arct. Alp. Res., *5*, 3, 2, p. A3–A18.

Troll, C., 1973b: High mountain belts between the polar caps and the equator: their definition and lower limit. Arct. Alp. Res., *5*, 3, 2, p. A19–A27.

Wardle, P., 1971: An explanation for alpine timberline. New Zealand Journal of Botany, *9*, p. 371–402.

Wardle, P., 1974: Alpine timberlines. In Ives, J.D., Barry, R.G. (eds): Arctic and alpine environments. Methlenj, London, p. 371–402.

Received 18. 11. 2003