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Forest cover in watershed of mountain stream Javorinka in 2010

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Abstract. Tatra forests in the watershed of the river Javorinka represent a complex of natural and man-made forest habitats. Utilizing geographic information systems, we were able to identify four classes of forest based on aerial photographs from 2010. These forests are spatially connected with abiotic properties as well as properties of individual stands, according to the forest stand map. Around 20 % of forest cover was in some way associated with the degradation of forest stands. The most degraded stands were alpine spruce forests (*Sorbeto-Piceetum*), especially in the higher age classes, on the southern to western slopes and in places where the water accumulation flow conditions were lower. We are of the opinion that the natural degradation of these forest communities occurs in the area, and this degradation may be exacerbated by the effects of a changing climate.

Key words: Watershed of mountain stream, Javorinka, forests, forest degradation, GIS, Tatra Mountains

Introduction

The fact that we are currently witnessing global climate change is becoming increasingly obvious and acceptable, and changes are observed the world over. In Europe, the Paris Agreement has the professional community searching for synergies between adaptation and mitigation and linking them to sustainable development goals (Harrison *et al.* 2019). This issue is also closely related to the benefits of biodiversity, nature protection (Prober *et al.* 2019) and sustainable forestry (Sesana *et al.* 2018). It is necessary to adapt ecosystem management and conservation practices to climate change goals, but widely accepted goals are geared toward the ecosystem's recovery to historical form, or to adaptation in changed conditions. These types of habitat-based measures are limited in efficiency (Wessely *et al.* 2017). Most tree species currently face a significant decrease in suitable habitat area (Dyderski *et al.* 2018). Assuming limited migration possibilities, ecological consequences would be serious for forestry, nature conservation and provided ecosystem services (Fleischer *et al.* 2017). Climate change varies regionally (Lindner *et al.* 2014). In a study by Sousa-Silva *et al.* (2018) authors pointed to general awareness among foresters (from Europe countries), with almost three quarters convinced that climate change will impact their forest, but only one-third reporting modified management practices. Though approaches vary throughout the European Union, in Slovakia more than half of foresters have already changed their management plans. The primary issue for this ecosystem is that current forests will have to cope with future climate conditions (Wagner *et al.* 2014).

In the Tatra Mountains, current forest composition exhibits a higher occurrence of spruce, reflecting postglacial development of vegetation and human activity from the 16th century. Lower elevations were completely clear-cut and replanted. Tatra forests were also periodically affected by windstorm disturbances (Koreň 2005; Koreň *et al.* 1997; Zielonka *et al.* 2009, 2010) and the consequences of bark beetle degradation (Fleischer *et al.* 2009). In the European context, some authors (Gregow *et al.* 2017; Brázdil *et al.* 2018) refer to increased occasion and impact of these events over last few decades. Bebi *et al.* (2017) observed changes in forest cover in the Alps due to disturbance, and noticed that forests established before 1880 were more damaged, perhaps due to their age increasing susceptibility to damage. Climate drivers, topography, human influence, and forest structure may also play a part. Some studies from the Research Station of TANAP (Fleisher and Koreň 1993, 1995) observed that forest stands were in poor condition, especially at higher elevations, prior to the most recent large windstorm (2004) in the Tatras. Naturalness and other parameters of these damaged forests have already been discussed (Koreň, 2005; Melicharová *et al.* 2007; Minár *et al.* 2009; Fleisher and Homolová 2011) with consequences to future management objectives and adaptation to climate change (Fleischer *et al.* 2009). Results from established reference plots (Fleischer 2008) after 15 years show that forest recovery was successful with higher tree diversity and a higher share of *Larix decidua* (Šebeň and Konôpka 2019). While the abundance of species increased at all sites, those with fallen trees were left with lower diversity and a higher prevalence of spruce individuals (Homolová *et al.* 2019), which lead to the formation of vegetation structures (spruce monoculture) prone to decay from wind or insects. This development of natural forest communities could contrast with the generally accepted need to apply adaptation and mitigation measures in the management of forest ecosystems, but will be driven by new natural conditions, where surviving individuals will support the emergence of a new generation. Ferenčík (2019) pointed to increased degradation from bark beetle, which has affected 50 % of adult forest stands in recent history. He described that this "catastrophic situation" exists primarily in old forest stands (130-180 years) in almost all valleys in the Tatras, with an even higher occurrence in forest stands at 300 m that have sustained damage from wind already, and remain unmanaged. Prevalence of dry and dead trees will increase as the spatial extent and location of vertical climatic belts have shifted over the last 50 years (Łupikasza and Szypuła 2019) in the region. In recent decades, the annual air temperature has increased (Zeleňáková *et al.* 2018a, b) along with a slight amount of precipitation (Repel *et al.* 2021), but the trend of water runoff has not changed significantly (Bičárová and Holko 2013; Zeleňáková *et al.* 2013). Generally, skeletal soil without vegetation cover can filter more water and remaining soil moisture could evaporate faster due to higher temperatures or consumption by young stands (Gebhardt *et al.* 2014). The situation is critical because indicators of ecological stability in dominant alpine spruce forests, such as low tree species diversity, and higher share of biomass, as well as other abiotic conditions defined by topography are unfavourable (Fleisher and Homolová 2011).

More attention to the issue of forest degradation could encourage additional studies utilizing remote sensing (Jakuš *et al.* 2003; Havašová *et al.* 2015; Ochtyra 2020). In this study we focused on a basic spatial model determined by remote sensing, where we chose the coloured orthophoto mosaic of 2010, a year when consequences of forest degradation were fully evident in the Tatra Mountains. High resolution orthophoto mosaics with digital terrain models provide the ability to analyse spatial distribution data with regard to the damaged forest cover in relation to topography. The aim of this study is the analysis of forest cover in the watershed of Javorinka stream, with an emphasis on analysis of habitat conditions within the damaged forest. This is a pilot study, with the potential for more complex research on the entire mountain watershed area in the future.

Material and Methods

The Study area

The study area was comprised of the watershed of Javorinka stream, from mountain ridges to the crossing of road 66 in Podspády (Fig. 1). Javorinka stream originates in the Zadná Javorová valley of the High Tatras and flows to the Baltic Sea via Biela voda, Dunajec and Visla. The average annual flow is 1.8 $m^3.s^{-1}$ at the site where it crosses road 66 (SHMÚ 2007). The whole area is within Tatra National Park.

From a geomorphological perspective, the study area of the watershed belongs to three subdivisions within the Western Carpathians: High Tatras (south and west), Belianske Tatras (east) and Ždiar furrow (north). Its geological composition is varied. The southern part of the studied area was formed in the Paleozoic, older and younger Carboniferous, which is composed of tonalite granodiorites and

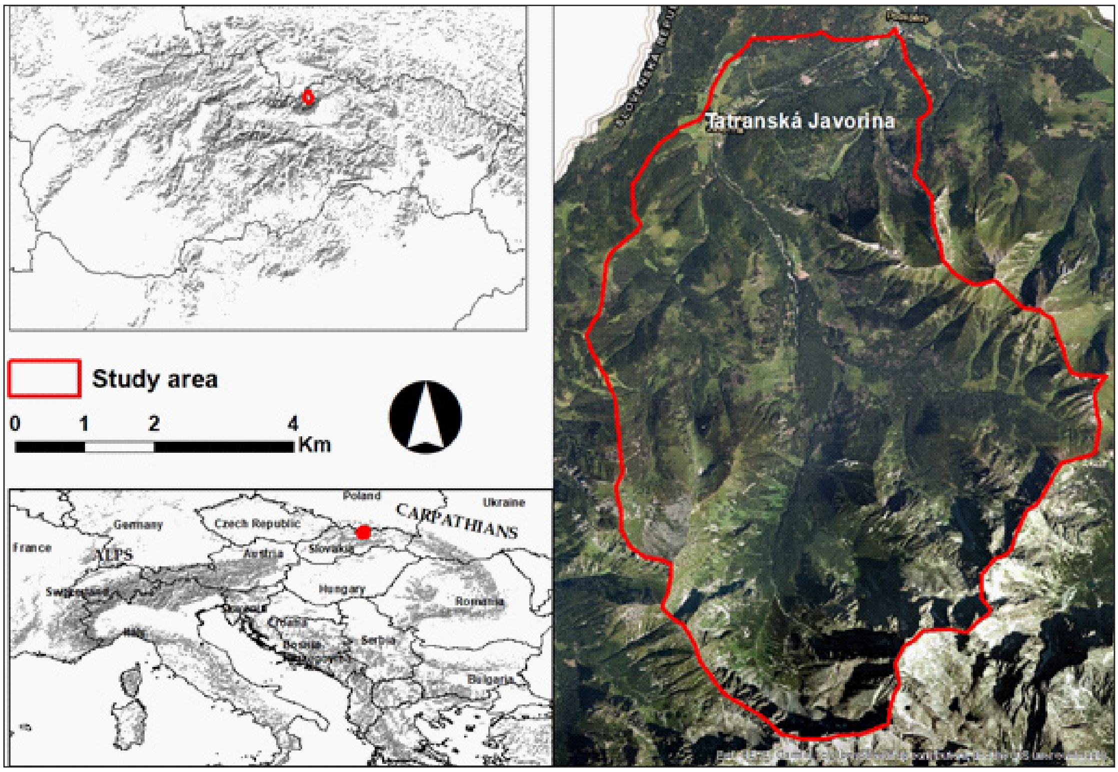

Fig. 1. Study area in watershed of mountain stream Javorinka (N49.22632°, E20.16171°).

granites. As we continue down the river, the surrounding hills are limestone and dolomites from the Middle Triassic period. The closer we get to the riverbed, the more the geological structure of the area changes to claystone, sandstone, shale and quartzite from the time of the younger Jurassic and older Cretaceous. The riverbed itself is formed of glacigenic sediments - gravel and boulders and deluvial-proluvial sediments - gravel and sand, which came to the surface in the Pleistocene (ŠGÚDŠ 2017). In the studied area we can observed altitude zonality of soil types, from rankers, rendzinas, pararendzina, cambisols, and podzols, to alluvial soils dominated by acid reaction, as well as neutral soils where silicates or carbonates elements are dominant (Bedrna and Račko 2000). The region is in a cold climatic area with continental weather patterns and typical features of the alpine climate. The annual average temperature in July is 16°C and total annual average precipitation 1512 mm. This region has significantly more precipitation compared to southern areas of the Tatra Mountains due to its windward position. This means that precipitation in Tatranská Javorina at 1030 m asl. is equal to precipitation on the south side of the Tatra Mountain at Skalnaté tarn, with an elevation of 1778 m asl. (see Bičárová and Holko 2013). Therefore, this area belongs to the cold and humid district.

Data collecting and processing

For the purpose of this study, we used aerial images (orthophoto mosaic) along with a reference system (s-jtsk) from year 2010. The orthophoto mosaic with high resolution (pixels with 0.5 x 0.5 m) was provided by the Geodetic and Cartographic Institute Bratislava (GCI). The layer of forest cover was manually digitalized (using edit tools) by ArcGis software (ESRI, USA) in a scale of approximately 1:1000. Four classes were used to identify forest cover in study area. Healthy forest (green, defined as a forest without visible degradation, young forest (light green), damaged forest (dark olivenite) and dry or dead forest (red). Damaged forests were identified as places where the forest was in a degradation stage, exhibiting fallen trees or clear-cut areas. These places were compared to aerial images from 2003. Forests that existed in 2003, but no longer exist the same capacity in 2010 were deemed damaged. Similarly, young forests were also identified through image comparison, in this case forest stands were observed in 2003 and in 2010. Forests identified for the first time in 2010 were considered new forests. Dry or dead forests were identified by the gray colour of the standing trees. After finishing manual digitalization, we obtained forest cover proportions of individual classes.

We analysed abiotic conditions according to a digital model of relief (DMR 3.5 from GCI 2018) using spatial analyst in ArcGis. Initially, we created a basic raster of elevation (m asl.), slope (degree), aspect (slope orientation), solar radiation (watt hours per square meter - WH/m^2) and water flow accumulation (potential surface precipitation build-up). The forest cover vector map was transformed to raster in same parameters as of DMR. One pixel represented 10 meters squared, and forest cover information was stored in pixels given

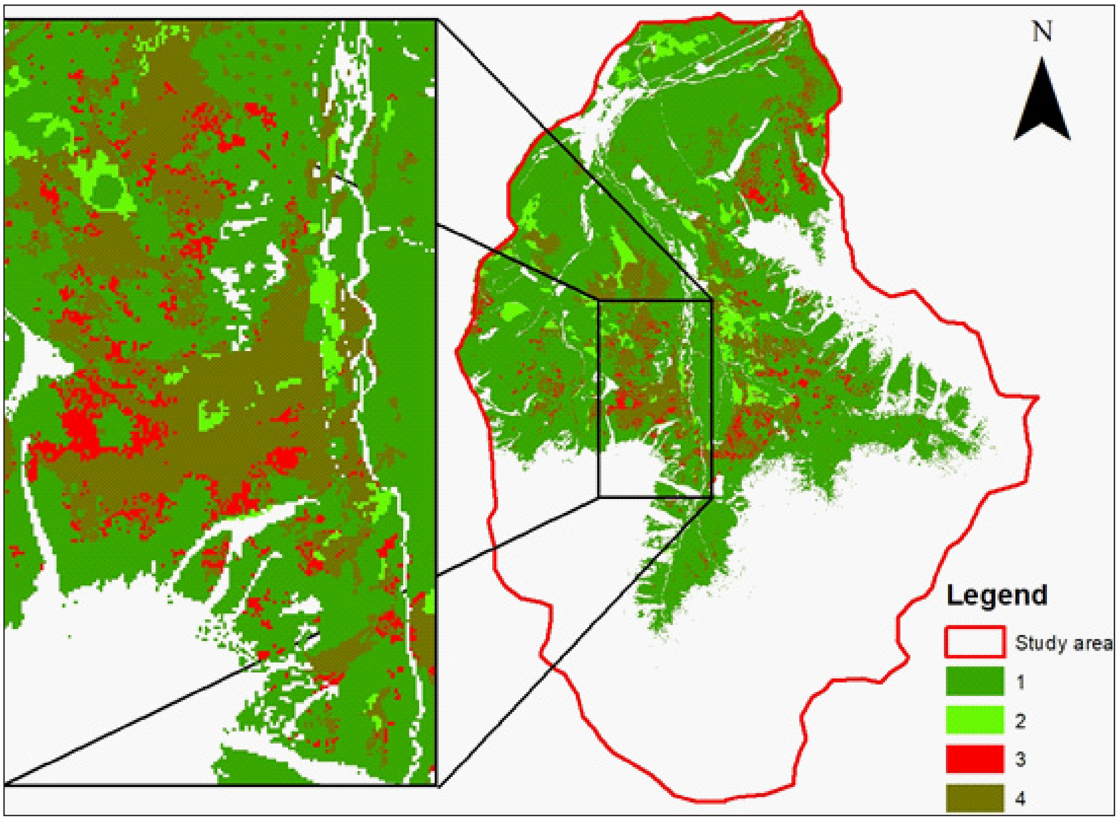

Fig. 2. Forest cover map in watershed of mountain stream Javorinka (1 - health forest; 2 - young forest; 3 - dry or dead forest; 4 - damaged forest).

from centroid position. This raster was then converted to points (centroids) and abiotic characteristics were extracted from the mentioned abiotic raster (derived from DMR). Finally, the point layer was spatially joined with layer of forest stands from National Forest Centre (NFC 2007). From these procedures we were able export table as a matrix for statistical evaluation.

Statistical analysis

The data matrix of forest cover for this region was evaluated by STATISTICA 8.0 (StatSoft Inc., USA). We used basic descriptive statistics, methods and analysis of variance One-Way ANOVA to identify potential differences between forest cover classes and selected abiotic variables extracted from DMR.

Results

The results of forest cover mapping according to the orthophoto mosaic from 2010 is shown in Fig. 2. White spots are places without forest cover, they include subalpine (dwarf pine stands), alpine (treeless) or subnival (bare rocks, debris) areas at higher elevations. At lower elevations we can distinguish meadows and urbanized parts of this mountain landscape. In total, forests covered 2 372 hectares (Table 1) out of the total watershed area of Javorinka stream (4733 ha), or approximately 50 %. In terms of forest class, 78.5 % forests identified as healthy forest (class 1), without visible damage to the forest structure. Damaged forests (class 4), defined as areas without trees or fallen trees, covered 329.44 ha. Dry or dead forest (class 3), defined as dry and dead standing trees, covered 78.14 ha. Young forests, which are often replanted areas that suffered from previous damage, covered 102.51 ha. All together, more than 21 % of forests in this area were impacted by various disturbances over the last few decades. Visually, sites with dry or dead forest are located around the existing damaged forest. This suggests that active forest management present in area is insufficient to counter disintegration of forest communities already underway.

Almost no differences were observed between forest classes and mean radiation values based on the studied abiotic factors (Table 1). The highest elevation forest occurrence was at an altitude or 1776 m, but forests were affected by disturbances were at maximum altitude level of 1597 m. In 2010, forests in this belt (179 m) were unaffected by ongoing forest degradation and forestry management. Although the mean elevation value is slightly higher (58 m) for the class of dry or dead forests, using One-Way ANOVA, we were able identify that mapped dry or dead forests occurred at higher elevations than damaged forests and sites that were replanted (Fig. 3a). This may be associated with increasing degradation of forests at higher elevations close to damaged forest areas. Dry and dead forests were also found on steeper slopes (Fig. 3b), indicating that this was a factor in their degradation. The biggest differences were observed in values of water flow accumulation, especially in the case of dry or dead forests, where we can see the possible effect of a water deficit (Fig. 3c). This means that forest stands identified as dry or dead, or young replanted stands were at sites where values of water flow accumulation were significantly lower. Based on an analysis of road distance, it is clear that young damaged forests tend to appear closer to roads (Fig. 3d), likely because new roads were built in places where logging was underway or other forestry management practices were utilized.

Differences in solar radiation between observed forest classes yielded average values (Table

Class	Area			Elevation	Slope	Radiation	Flow	Roads
1	1 862.08	ha	Mean	1 264	24	5 504	1 036	105
	78.50	%	Minimum	913	0	1 166	0	0
			Maximum	1 776	81	6 720	473 440	855
2	102.51	ha	Mean	1 212	22	5 679	349	64
	4.32	%	Minimum	936	0	3 239	0	0
			Maximum	1 470	48	6 547	249653	347
3	78.14	ha	Mean	1 322	26	5 477	103	103
	3.29	%	Minimum	929	1	1 815	0	0
			Maximum	1 589	77	6 617	130 969	638
4	329.44	ha	Mean	1 265	24	5 598	906	86
	13.89	%	Minimum	913	0	3 521	0	0
			Maximum	1 597	60	6 640	473 062	414
Total	2 372.17	ha	Mean	1 264	24	5 523	957	101
	100	%	Minimum	913	0	1 166	0	0
			Maximum	1 776	81	6 720	473 440	855

Table 1. The basic characteristics for individual classes of forest cover in watershed of mountain stream Javorinka (1 - health forest; 2 - young forest; 3 - dry or dead forest; 4 - damaged forest; Elevation (m asl.), Slope (degree), Radiation (WH/m^2), Flow accumulation (potential surface precipitation build-up), Roads (distance from roads in meters)).

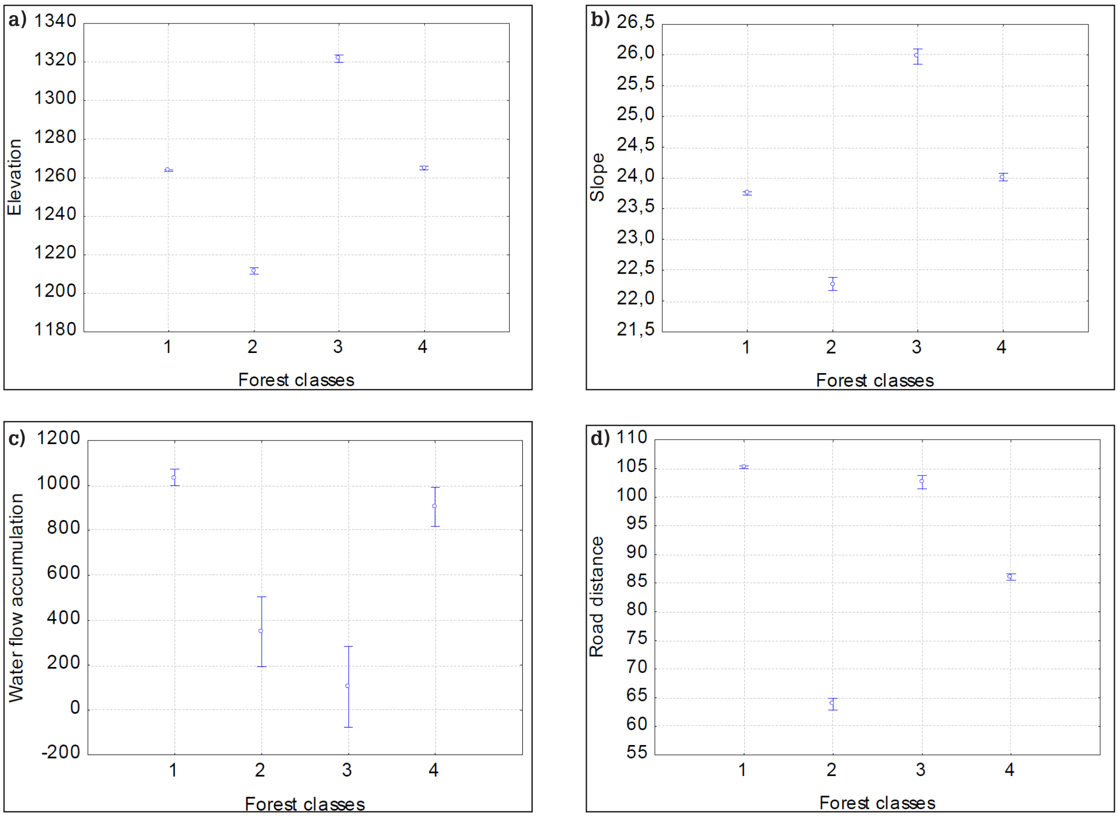

Fig. 3. Distribution of forest classes in relation to selected abiotic conditions. One-Way ANOVA (Means of least squares, vertical bars denote +/- standard errors); **a)** altitude (m asl.) F (3, 237 213) = 628.00, p = 0.001; **b)** slope (degree) F (3, 237 213) = 168.74, p = 0.001; **c)** water flow accumulation F (3, 237 213) = 14.257, p = 0.001; **d)** road distance (m) F (3, 237 213) = 807.87, p = 0.001; 1 - health forest; 2 - young forest; 3 - dry or dead forest; 4 - damaged forest.

1), although using the analysis of variation we achieved significant differences (F (3, 237213) = 484.60, p = 0.001) between classes, particularly between young and damaged forests and either healthy forests or and dry or dead forests. We looked into individual classes in relation to orientation of slope (aspect). Generally, forests cover slopes from north to east and from west to north (Fig. 4a) in the study area. Forest classes connected to forest degradation (classes 2, 3, 4) are mostly oriented on slopes from east to west with a higher presence on south facing slopes. While young forests are predominantly located on southeast or west slopes (likely as a result of forest regeneration), the dry or dead forest stands are at south and southwest slopes (Fig. 4b). South slopes are often warmer, but with increasing air temperature and evaporation during the day, the slopes from southwest to west may be more greatly impacted by water deficits.

Fig. 4. Distribution of forest classes in relation to orientation of slopes (aspect). **a)** distribution according to total area of individual forest classes in hectares; **b)** distribution of individual forest classes as percentage from total area of individual forest classes) 1 - health forest; 2 - young forest; 3 - dry or dead forest; 4 - damaged forest.

According to data from the National Forest Centre (Maps of forest stand) from 2007, older forest stands dominate in the studied watershed (Fig. 5). Approximately 71 % of forests are older than 100 years and 40 % are older than 150 years. Twenty eight percent of forest stands are around 70 years old. The most abundant species within forest stands in this region is alpine spruce (*Sorbeto-Piceetum*), comprising 55 % of the cover. Next, fir beech spruce stands (*Fageto-Abietum*) constitute a 19 % share of the total (Fig. 6). If we take these proportions into consideration, in conjunction with forest classes 3 and 4, then the alpine spruce forest stands were most affected by disturbances (Table 2).

If we look closely at stands of alpine spruce (*Sorbeto-Piceetum*), we can see that these stands are often older (Fig. 7). Approximately 45 % of total forest cover is represented by stands of alpine spruce in age classes older than 130 years, constituting more than 1066 ha. Healthy forests covered 753.41 ha, young forests 42.25 ha, damaged forests covered 205.53 ha and dry of dead forest covered 64.66 ha. This may possibly mean that more than 30 % of alpine spruce stands were affected by age-related degradation. The situation facing these stands is unfavourable in terms of climate change if take a close look at abiotic conditions (Fig. 8a-d). These stands predominantly exist on warm, sunny, waterless and steeper slopes, but at higher elevations, where due to lower temperatures and higher precipitation (clouds, misty, rain, snow) these stands have optimal conditions for life.

Types of forest stands	1	2	3	4
Abieto-Piceetum	3.12	**14.49**	0.69	0.23
Alnetum-incanae	1.22	0.00	0.03	2.31
Cembreto-Mughetum	0.50	0.16	2.42	0.44
Fageto-Abietum	**22.22**	**14.21**	3.22	7.63
Fageto-Piceetum	2.77	1.09	1.59	1.79
Fagetum abietino-piceosum	1.83	3.18	0.06	4.42
Fagetum humile	0.93	5.81	0.12	0.12
Mughetum acidofilum	13.46	0.61	3.66	1.13
Piceetum abietinum	1.41	0.70	0.01	0.95
Ribeto-Mughetum	2.59	1.28	3.21	0.53
Sorbeto - Piceetum	**49.08**	**58.46**	**84.94**	**80.44**

Table 2. Percentage of individual types of forest stands in relation to monitored forest classes in watershed of mountain stream Javorinka (1 - health forest; 2 - young forest; 3 - dry or dead forest; 4 - damaged forest).

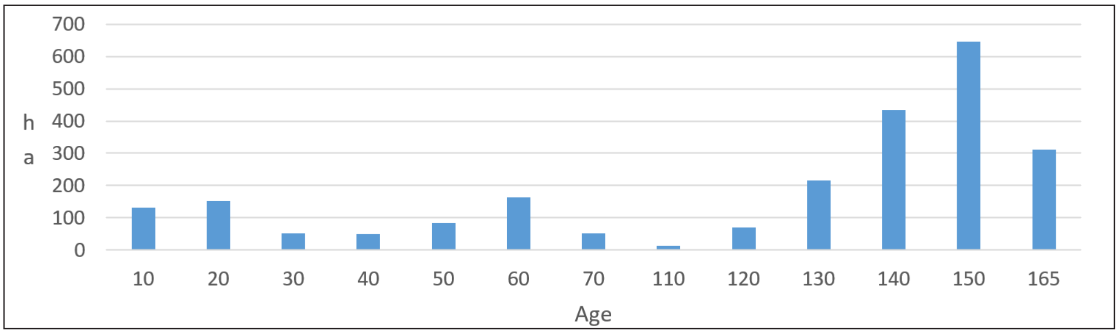

Fig. 5. Age classes of forest stands in watershed of mountain stream Javorinka.

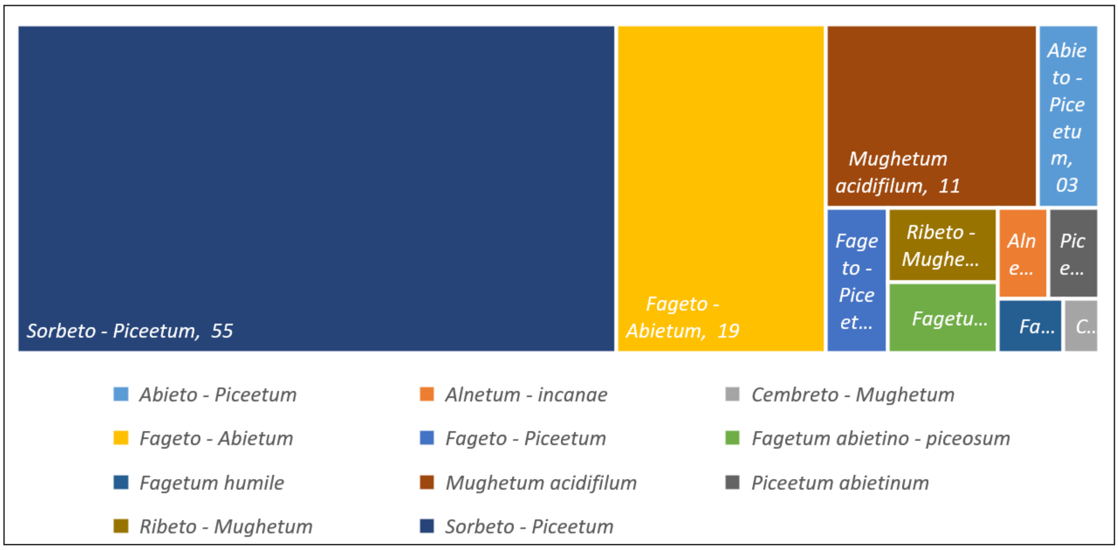

Fig. 6. Types of forest stands in watershed of mountain stream Javorinka.

Fig. 7. Age structure (classes) of alpine spruce (*Sorbeto-Piceetum*) forest stands in watershed of mountain stream Javorinka. All - all identified forest classes; 3 - dry or dead forests; 4 - damaged forests.

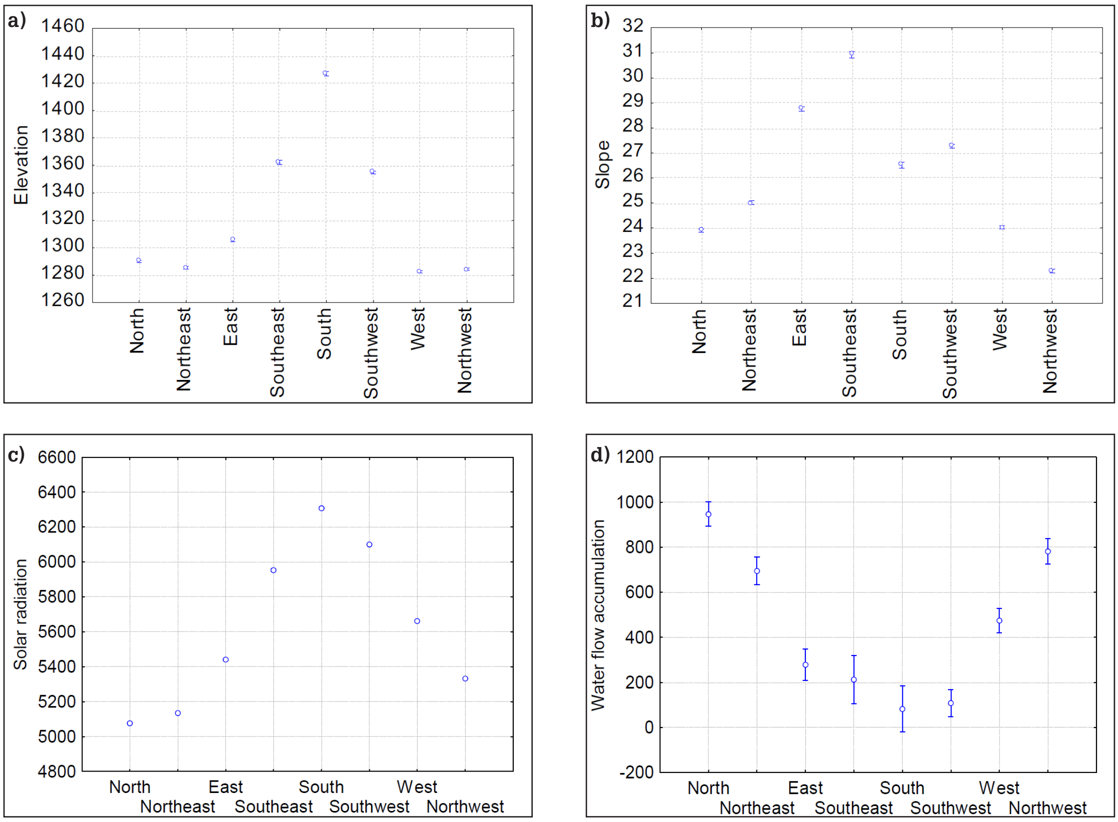

Fig. 8. Distribution of alpine spruce (*Sorbeto-Piceetum*) forest stands in relation to selected abiotic conditions. One-Way ANOVA (Means of least squares, vertical bars denote +/- standard errors); **a)** – altitude (m asl.) $F\ (7, 130\ 520) = 1\ 626.9$, $p = 0.001$; **b)** – slope (degree) $F\ (7, 130\ 520) = 983.94$, $p = 0.001$; **c)** – solar radiation (Wh/m^2) $F\ (7, 130\ 520) = 12\ 162$, $p = 0.001$; **d)** – water flow accumulation $F\ (7, 130\ 520) = 25.236$, $p = 0.001$.

Discussion

It is not surprising that forests in this area are in a state of degradation. Naturally, spruce forests expanded to the narrow valleys of the Tatra Mountain during the dry boreal era (6800-5500 BC) (Jankovská 1988). However, current composition of stands reflect postglacial development of vegetation as well as natural development associated with climate change over time in specific topography conditions, as a result of human interference in forest communities starting in the 16th century. Formation of settlements in the Tatras during the 18th and 19th centuries was a crucial period for forests (Fleischer *et al.* 2009). Lower parts of Tatra valleys as well as our study area were deforested. There is no doubt about that deforested areas were replanted, but the replanted forests lost structural diversity (Koreň *et al.* 1997), and potentially in situ autochthonous species, which have evolved over the ages and could thus be more resilient in these extreme conditions. In the study area, larger windfalls occurred in 1936, 1950, 1959 and throughout 1966-1971, paired with the effects of bark beetle overgrowth (Koreň *et al.* 1997). Starting in the 1970s foresters systematically worked at divided stands and tried to improve the health status of individual forest stands. However, these efforts have failed, and to-day we are witnessing the disintegration of forest communities, predominantly at sites which have experienced long-term impacts by man. There are many reasons that the condition of forests in the region requires additional discussion and consideration. On the other hand, we must consider that periodical windstorms combined with bark beetle overgrowth are not a new phenomenon in the Tatra region (Koreň 2005; Zielonka *et al.* 2009, 2010). These are the kind of natural disturbances necessary to maintain the dynamic of the entire forest ecosystem (Whittaker 1975). This is especially true in the Western Carpathians, where huge forest fires are limited. In this sense, it is more appropriate to think about the catastrophic climax by Odum (1977) as it relates to our study area.

Systematic forestry activities and the indirect influence of human activities from the industrial sphere (pollution) also play a role in our perception of how these stands may persist in the future within this region (Koreň *et al.* 1997). If we take a close look at natural development of alpine spruce forests (*Sorbeto-Piceetum*) in relation to stand structure and biomass, according to Korpeľ (1986), the optimum age stage of these stands is somewhere from 140 to 180 years. Recently, Ferenčík (2019) pointed to a "catastrophic situation" in old forest stands (130-180 years) in almost all Tatra valleys, because of lack management after wind disturbances with bark beetle consequences. We observed significant forest degradation in old forest classes. Koreň *et al.* (1997) have discussed the issue of old forest stands paired with the absence of middle age classes in this area, and their fears came to pass. On the other hand, we must consider that the optimum age curve could be reduced due to less favourable conditions and pollution. A study by Šoltes *et al.* (1992) shows that the Javorinka watershed is the most heavily polluted area in the Tatra Mountains, where stands affected by bark beetle degradation were positively correlated with heavy metals. Defoliation analysis indicates that approximately 30 % of forest stands were affected, with an increasing trend (Koreň *et al.* 1997), especially in lower elevation sites of our study area. Generally, defoliation as a result of contamination increases with elevation. The structure of forest stands may also reduce their optimum age curve, because habitats with poor structure diversity are less resistant to disturbances (Jactel *et al.* 2017). Our analysis confirms that alpine spruce forests dominantly occurred at sites with unfavourable abiotic characteristics in terms of climate change, and where water stress plays a significant role. If we look at the data from the Slovak Hydrometeorological Institute, there is a significantly positive annual trend in air temperature (1962-2014) measured at all climatic stations, especially at sites with higher elevation (Lomnický peak - 2635 m asl., Skalnaté tarn 1778 m asl.) between April and August (Zeleňáková *et al.* 2018a,b). A significant decrease in the number of days without precipitation occurred in Tatranská Javorina between 1970 and 2019). A significant decrease in the number of days without precipitation, a significant increase in annual precipitation as well as maximum daily precipitation (Repel *et al.* 2021) were measured. Precipitation increased mostly at spring. This means that temperature increased along with the amount of precipitation, but the trend of water runoff (1961-2010) has not changed significantly in recent decades (Zeleňáková *et al.* 2013, Bičárová and Holko 2013). This indicates that something is happening within the water cycle. Here we can consider additional features of monitored forest habitats. Areas with decaying biomass (dead fallen or standing trees) retain more water than clear-cut areas or areas where fallen and dead trees were extracted. Old forests with higher biomass retain more water; younger forest stands may consume more water for their growth; or more water tends to evaporate. Trees felled by wind or affected by bark beetle were predominantly extracted from stands by active forest management connected to bark beetle risk prevention. The proportion of old forest stands decreased due to disturbances. Young stands only covered 4.23 % of the area. This indicates that higher evapotranspiration is occurring, likely because the synergic effect of higher temperature and evapotranspiration might lead to higher landscape drying effect in the region, especially at the end of vegetation period. This trend of increased evapotranspiration was observed across Europe (Teuling *et al.* 2019), but water flow rate only increased where was enough precipitation. Another logical explanation for a lack of increase to runoff is the rocky soil, that without forest cover may be more absorbent. Therefore, we suggest carefull consideration of forest management practices with regard to a water balance assessment in this context of rising temperatures and natural dynamics of forest communities.

Current degradation of forest communities in this region are affected by a combination of various factors. In these complex conditions foresters must decide whether to direct change, or remain spectators, allowing changes to occur based on natural selection, and biodiversity.

Conclusion

This study analysed forest cover in the mountainous watershed area of the Javorinka river. Using the Geographic information system with high resolution data, we were able to identify four quality classes of forest, which were spatially compared with abiotic characteristics derived from a digital relief model and data from maps of forest stands. Results pointed to a general tendency of forest stand degradation. In total more than 20 % of forests in this area have been impacted by various disturbances in the last few decades. These stands covered mostly slopes oriented from east to west with a higher occurrence on south faced slopes. The dry or dead forest stands were most often located around the existing damaged forest areas, as well as on higher and stepper slopes where water flow accumulation was significantly low. The most degraded stands were alpine spruce forests (*Sorbeto-Piceetum*). These stands were commonly situated on warmer, sunnier, drier and steeper slopes. At higher elevations, with corresponding lower temperatures and higher precipitation (clouds, misty, rain, snow), these stands have the optimal conditions for life. On the other hand, outlook is unfavourable for these stands, based on aspects of stand structure, climate change and abiotic characteristics. We maintain that the natural degradation of these forest communities has been accelerated by the effects of a changing climate and active forestry management in the region. It is questionable whether this degradation can be mitigated, as current forests will still need to cope with future unpredictable climate conditions.

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References

Angelovičová, Bebi, P., Seidl, R., Motta, R., Fuhr, M., Firm, D., Krumm, F., Conederag, M., Ginzlerg, C., Wohlgemuthg, T. and Kulakowski, D. 2017: Changes of forest cover and disturbance regimes in the mountain forests of the Alps. *Forest Ecol. Manag.*, **388**: 43-56.

Bedrna, Z. and Račko, J. 2000: Príspevok k pedogeografii Belianskych Tatier. *Geografický časopis*, **52**: 323-336.

Bičárová, S. and Holko, L. 2013: Changes of characteristics of daily precipitation and runoff in the High Tatra Mountains, Slovakia over the last fifty years. *Contrib. to Geophys. Geodesy*, **43**: 157-177.

Brázdil, R., Stucki, P., Szabó, P., Řezníčková, L., Dolák, L., Dobrovolný, P., Tolasz, R., Kotyza, O., Chromá, K. and Suchánková, S. 2018: Windstorms and forest disturbances in the Czech Lands: 1801–2015. *Agr. Forest Meteorol.*, **250**: 47-63.

Dyderski, M.K., Paź, S., Frelich, L.E., and Jagodziński, A.M. 2018: How much does climate change threaten European forest tree species distributions? *Glob. Change Biol.*, **24**: 1150-1163.

Ferenčík J. 2019: Prehľad výskumu podkôrneho hmyzu. *Štúdie o Tatranskom národnom parku*, **46**: 77-86.

Fleischer P. and Koreň M. 1995: Forest health conditions in Tatra Biosphere Reserve. *Ekologia (Bratislava)*, **14**: 445-459.

Fleischer P. and Koreň M. Jr. 1993: Application of GIS and remote sensing for forest health detection in Tatra National Park. International symposium application of remote sensing in forestry, pp. 93-100. Technical University, Zvolen.

Fleischer P., M. Koreň, J. Škvarenina and V. Kunca 2009: Risk Assessment of the Tatra Mountains Forest. In: *Bioclimatology and Natural Hazards*, (ed. K. Strelcová), pp. 145-154. Springer Science+Business Media B.V.

Fleischer, P. 2008: Windfall research and monitoring in the High Tatra Mts., objectives, principles, methods, and current status. *Contrib. to Geophys. Geodesy*, **38**: 233-248.

Fleischer, P. and Homolová, Z. 2011: Long-term research on ecological condition in the larch-spruce forests in High Tatras after natural disturbances. *Lesnícky Časopis*, **57**: 237-250.

Fleischer, P., Pichler, V., Fleischer Jr. P., Holko, L., Máliš, F., Gömöryová, E., Cudlín, P., Holeksa, J., Michalová, Z., Homolová, Z., Škvarenina, J., Střelcová, K. and Hlaváč, P. 2017: Forest ecosystem services affected by natural disturbances, climate and land-use changes in the Tatra Mountains. *Clim. Res.*, **73**: 57-71.

GCI 2018: Digital model of relief 3.5. Geodetic and Cartographic Institute Bratislava, Online: https://www.geoportal.sk/sk/zbgis_smd/na-stiahnutie (retrieved 13.3.2021).

Gebhardt, T., Häberle, K.H., Matyssek, R., Schulz, C., and Ammer, C. 2014: The more, the better? Water relations of Norway spruce stands after progressive thinning. *Agr. Forest Meteorol.*, **197**: 235-243.

Gregow, H., Laaksonen, A., and Alper, M. E. 2017: Increasing large scale windstorm damage in Western, Central and Northern European forests, 1951–2010. *Sci. Rep-UK*, **7**: 1-7.

Harrison, P. A., Dunford, R. W., Holman, I. P., Cojocaru, G., Madsen, M. S., Chen, P. Y., Pedde, S. and Sandars, D. 2019: Differences between low-end and high-end climate change impacts in Europe across multiple sectors. *Reg. Environ. Change*, **19**: 695-709.

Havašová, M., Bucha, T., Ferenčík, J., and Jakuš, R. 2015: Applicability of a vegetation indices-based method to map bark beetle outbreaks in the High Tatra Mountains. *Ann. For. Res.*, **58**: 295-310.

Homolová Z., Kyselová Z., Šoltés R. 2019: Postdisturbančný vývoj vegetácie vo Vysokých Tatrách. *Štúdie o TANAP-e*, **46**: 27-37.

Jactel, H., Bauhus, J., Boberg, J., Bonal, D., Castagneyrol, B., Gardiner, B., Gonzalez-Olabarria, J.R., Koricheva, J., Meurisse, N. and Brockerhoff, E.G. 2017: Tree diversity drives forest stand resistance to natural disturbances. *Curr. For. Rep.*, **3**: 223-243.

Jakuš, R., Grodzki, W., Ježík, M., and Jachym, M. 2003: Definition of spatial patterns of bark beetle *Ips typographus* (L.) outbreak spreading in Tatra Mountains (Central Europe), using GIS. In: *Ecology, Survey and Management of Forest Insects*, Proceedings of the conference, pp. 25-32. USDA Forest Service, GTR NE-311.

Jankovská, V. 1988: A reconstruction of the Late-Glacial and Early-Holocene evolution of forest vegetation in the Poprad basin, Czechoslovakia. *Folia geobotanica & phytotaxonomica*, **23**: 303-319.

Koreň, M. 2005: Windfall in the forest of the TANAP, reasons and consequences. Proceedings from seminar: *Actual problems in forest conservation*, pp. 46–55. Banská Štiavnica 28–29.04.2005.

Koreň, M., Fleischer, P. and Turok J. 1997: Príčiny podkôrnikovej kalmity v ochrannom obvode Javorina a návrh ozdravných opatrení. *Štúdie o TANAP-e*, **36**: 113-188.

Korpeľ Š. 1986: *Pestovanie lesa*. Edičné stredisko VŠLD Zvolen.

Lindner, M., Fitzgerald, J.B., Zimmermann, N.E., Reyer, C., Delzon, S., van der Maaten, E., Schelhaas, M.J., Lasch, P., Eggers, J., van der Maaten-Theunissen, M., Suckow, F., Psomas, A., Poulter, P. and Hanewinkel, M. 2014: Climate change and European forests: What do we know, what are the uncertainties, and what are the implications for forest management? *J. Environ. Manage.*, **146**: 69-83.

Łupikasza, E. and Szypuła, B. 2019: Vertical climatic belts in the Tatra Mountains in the light of current climate change. *Theor. Appl. Climatol.*, **136**: 249-264.

Melicharová, A., Schneider, J., Mikita, T., Celer, S., Kupec, P., and Vyskot, I. 2007: On the possibility of usage of GIS for ecological damage evaluation, demonstrated on example of the wind calamity in the High Tatra National Park. *Folia Oecologica*, **34**: 125-145.

Minár, J., Falan, V., Bánovský, M., Damankošová, Z., and Kouch, M. 2009: Influence of site conditions on the windstorm impast: a case study of the High Tatras foothills in 2004. *Landform Analysis*, **10**: 95-101.

NFC 2007: Map of forest stands. National Forest Centre. Online: https://gis.nlcsk.org/islhp/ (retrieved 17.4.2021).

Ochtyra, A. 2020: Forest Disturbances in Polish Tatra Mountains for 1985–2016 in Relation to Topography, Stand Features, and Protection Zone. *Forests*, **11**: 579-593.

Odum, E.P. 1977: The emergence of ecology as a new integrative discipline. *Science*, **195**: 1289–1293.

Prober, S.M., Doerr, V.A., Broadhurst, L.M., Williams, K.J. and Dickson, F. 2019: Shifting the conservation paradigm: a synthesis of options for renovating nature under climate change. *Ecol. Monogr.*, **89**: e01333.

Repel, A., Zeleňáková, M., Jothiprakash, V., Hlavatá, H., Blišťan, P., Gargar, I. and Purcz, P. 2021: Long-

term analysis of precipitation in Slovakia. *Water*, **13**: 952-965.
Šebeň, V. and Konôpka, B. 2019: Vývoj obnovy kalamitiska vo Vysokých Tatrách do roku 2019 podľa terestrického monitoring. *Štúdie o Tatranskom národnom parku*, **46**: 9-25.
Sesana, E., Gagnon, A. S., Bertolin, C. and Hughes, J. 2018: Adapting cultural heritage to climate change risks: perspectives of cultural heritage experts in Europe. *Geosciences*, **8**: 305.
ŠGÚDS 2017: Geologická mapa Slovenska M 1:50 000 [online]. Štátny geologický ústav Dionýza Štúra, Bratislava. Online: http://apl.geology.sk/gm50js. (retrieved 10.4.2021).
SHMÚ 2007: Priemerný ročný prietok, maximálny kulminačný prietok, minimálny priemerný denný prietok a priemerné mesačné prietoky v roku 2007. Slovenský hydrometeorologický ústav, Bratislava. Online: http://www.shmu.sk/File/kvantPV2007/mes_extrQ2007_Poprad.pdf (retrieved 16.4.2021).
Šoltés, R., Šoltésová, A. and Kyselová, Z. 1992: Vplyv emisií na nelesnú vegetáciu Vysokých a Belianských Tatier. *Zborník prác o TANAP-e*, **32**: 307-334.
Sousa-Silva, R., Verbist, B., Lomba, Â., Valent, P., Suškevičs, M., Picard, O., Hoogstra-Klein, M.A., Cosofret V.C., Bouriaud, L., Ponette, Q., Verheyen, K. and Muys, B. 2018: Adapting forest management to climate change in Europe: Linking perceptions to adaptive responses. *Forest Policy Econ.*, **90**: 22-30.
Teuling, A.J., de Badts, E.A.G., Jansen, F.A., Fuchs, R., Buitink, J., Hoek van Dijke, A.J. and Sterling, S.M. 2019: Climate change, reforestation/afforestation, and urbanization impacts on evapotranspiration and streamflow in Europe, *Hydrol. Earth Syst. Sci.*, **23**: 3631-3652.
Wagner, S., Nocentini, S., Huth, F. and Hoogstra-Klein, M. 2014: Forest management approaches for coping with the uncertainty of climate change: trade-offs in service provisioning and adaptability. *Ecol. Soc.*, **19**: 32-48.
Wessely, J., Hülber, K., Gattringer, A., Kuttner, M., Moser, D., Rabitsch, W., Schindler, S., Dullinger, S. and Essl, F. 2017: Habitat-based conservation strategies cannot compensate for climate-change-induced range loss. *Nat. Clim. Change*, **7**: 823-827.
Whittaker, R.H.W. 1975: Communities and ecosystems. Macmillan, New York, NY, US.
Zeleňáková, M., Purcz, P., Blišťan, P., Vranayová, Z., Hlavatá, H., Diaconu, D.C. and Portela, M.M. 2018a: Trends in precipitation and temperatures in Eastern Slovakia (1962–2014). *Water*, **10**: 727-753.
Zeleňáková, M., Purcz, P., Soľáková, T. and Demeterová, B. 2013: Analysis of trends of low flow in river stations in eastern Slovakia. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis*, **60**: 265-274.
Zeleňáková, M., Soľáková, T., Purcz, P. and Simonová, D. 2018b: Hydrological drought occurrence in Slovakia. In: *Water Resources in Slovakia: Part II*, pp. 69-90. Springer, Cham.
Zielonka, T., Holeksa, J., Fleischer, P. and Kapusta, P. 2010: A tree ring reconstruction of wind disturbances in a forest of the Slovakian Tatra Mountains, Western Carpathians. *J. Veg. Sci.*, **21**: 31-42.
Zielonka, T., Holeksa, J., Malcher, P. and Fleischer P. 2009: A two-hundred-year history of spruce - larch stand in the Slovakian High Tatras damaged by windstorm in 2004. In: *Windfall research in TANAP-2008* (eds. P. Fleisher and F. Matejka), pp. 269–274. Geophysical Institute of the Slovak Academy of Sciences, Research Station of the TANAP, State Forest of TANAP, Slovakia.

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