Research Article

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Umbrisols at Lower Altitudes, Case Study from Borská lowland (Slovakia)

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Abstract: Umbrisols generally develop in a cool and humid climate. Therefore, occurrence of these soils in the Borská lowland of southwestern Slovakia is very uncommon, and this inspired the aim of this paper: Analysis of the natural conditions suitable for Umbrisol development. Umbrisols in the Borská lowland developed from aeolian quartz sands accumulated on Neogenne marine clay sediments. Their occurrence is connected with the groundwater table relatively close to the ground surface and this particularly determines Umbrisol genesis in this area. Sufficient input via organic matter is an important factor for formation of the umbric horizon, and only the rich herbaceous undergrowth of the prevailing planted pine and mixed pine-oak forests is capable of providing it. A growth of diep-rooted grass is closely connected with higher soil moisture content, and quite moist areas occur in the deeper inter-dunes depressions. Constant soil moisture in these sites is facilitated by water capillary elevation. While Umbrisols are transformed to Arenosols at increased altitude, they can be transformed to Gleysols in deep depressions. Herein, induced polarization provided suitable geophysical method for detection of arenic Umbrisol inclusions. Sharp transformation of the humus layer to dry non-polarized aeolian quartz sands enabled the surface horizon to be distinguished by induced polarization

Keywords: soil organic carbon stock, intrazonal soils, Podzols, arenic/aeolian sands, ground water, geophysical measurements

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1 Introduction

Umbrisols have a thick mineral surface horizon rich in dark organic matter and low base saturation somewhere within the first metre [1]. These soils are frequently associated with acidic and strongly-leached basic parent material and they generally develop in a cool and humid climate; especially in mountainous regions with high rainfall and extensive leaching [2]. The formation of Umbrisols therefore requires an accumulation of organic matter which is significantly present in areas with abundant plant cover. Umbrisols have umbric, mollic or hortic horizon.

Umbrisols with mollic or hortic horizon are outside the scope of the present paper. Umbric horizon has the following characteristics; the horizon must be at least 20cm thick and have ≥ 0.6% soil organic carbon (SOC); a Munsell colour value of ≤ 3 moist and ≤ 5 dry and a chroma of ≤ 3 moist and a base saturation of < 50% on weighted average, by 1 *M* NH_4OAc at pH 7 [1]. The soil reaction is also crucial for field identification, because most umbric horizons have a maximum acidic soil reaction (pH_{water}) of 5.5 which provides base saturation under 50%.

The World Reference Base for Soil Resources 2014 (WRB) lists several soils with umbric horizon which are classified under Umbric, not Umbrisol. These include Stagnosols, Planosols, Podzols and Gleysols [1]. The majority of soils currently classified as Umbrisols were classed Humic Cambisols in the 1974 FAO–Unesco soil map, and this classification is complemented by the soil unit of Umbric Regosols [3]. Humic Cambisols have an umbric surface horizon thicker than 25 cm when a sub-surface cambic horizon is absent [4]. Interestingly, although the umbric horizon (epipedon) also exists in the U.S. Soil Taxonomy, this system does not have a corresponding Soil Order, and the majority of Umbrisols there are classified as Entisols or Inceptisols [5].

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Many studies have described the global occurrence of Umbrisols and soils with an umbric horizon [6–8]. Umbrisols dominate European soils of the Iberian Peninsula, in the hilly terrain of the Cantabria Mountains extending to the Atlantic Ocean, and are also prevalent in the Icelandic and Scottish Highlands, the Pyrenees [9, 10], the Massif Central [11], the Alps [12], the Appenines [13], the Southern Carpathians and the Bulgarian Pirin Mountains [14]. Umbrisols at lower altitudes are present on the acid igneous and metamorphic rocks in the Ruhr and Moselle basin (Germany), in Brittany (France), on fluvio-glacial deposits in Denmark [15] and also in Poland [16]. In addition, the occurrence of soil associations with inclusion or predominance of Umbrisols is predicted for all Central and Eastern European countries [2, 17, 18].

Although the Umbrisol Reference Soil Group has only recently been included as a new soil group in national soil classification systems, including Central and Eastern European countries, it has been part of the Romanian System of Soil Taxonomy as Nigrosol and Humosiolsol genetic types since 2000 [19], and they are newly included in the Slovak soil classification system. The Slovak system classifies Umbrisols as soils with umbric horizon, and all other diagnostic horizons except cambic are absent. Umbrisols can have a layer starting at ≥ 50cm from the mineral soil surface with its lower limit at ≤ 100cm, and also have reducing conditions in some sublayers. Compared to WRB standards, the umbric horizon must be over 20cm thick and have ≥ 1.0% soil organic carbon content (SOC) and three additional combined humus quality conditions; for example a carbon to nitrogen ratio (C:N ratio) > 12, humic acids to fulvic acids ratio (C_{HK}:C_{FK}ratio) < 1 and colour quotient (Q(4/6)) > 3 for humic acids and > 4 for humus substances [20].

Systematic research of Umbrisols and soils with umbric horizon in the Slovak Western Carpathians began in 2008 (The initial research was supported by Scientific Grant Agency of the Ministry of Education of the Slovak Republic and the Slovak Academy of Sciences under contract VEGA 1/0254/08). Dlapa *et al.* [21], Bedrna *et al.* [22] and Bedrna *et al.* [23] performed initial studies based on physical, chemical and, in some cases biological analysis of umbrisol profile features.

One of the first recorded occurrences of Umbrisols in Slovakia was at low altitudes in the Borská lowland [24] and this raised questions about which soil forming factors are essential for Umbrisol formation. Are these factors similar to those in mountain regions? A positive answer is suggested by the rare occurrence of Podzols in this region [25]. Podzols presence is related to Slovak altitudinal zonation, so to test this hypothesis we performed detailed soil mapping and monitoring of the natural environment in two selected Borská lowland localities; the Šajdíkove Humence I and Šajdíkove Humence II sites. Although research results did not absolutely confirm the hypothesis, their generalisation allowed prediction mapping of Umbrisols in the entire Borská lowland; with expectation that our methods and results will simplify future soil mapping.

Umbrisols rich in humus are therefore logical counterparts of slightly leached Chernozems, Kastanozems and Phaeozems with a chernic or mollic horizon and high base saturation. The umbric horizon depth and high SOC content provide Umbrisol areas with higher SOC stocks, and although these areas are rarely used as agricultural land, Umbrisols are important components of the carbon cycle and deserve increased attention and protection.

2 Study site

The Borská lowland forms the central and southern parts of the Záhorie Lowland geomorphological area located in the peripheral part of the Vienna Basin between the Morava River and the Western Carpathian Malé Karpaty Mts. (Little Carpathians). The lowland has warm-summer humid continental climate, without significant difference in precipitation between seasons. This area's 9.5 °C average annual temperature and the 550 to 600mm average annual precipitation. Aeolian sand dunes of quartz sands are the dominant landforms in the elevated central part of the Borská lowland (Bor). The Bor gently protrudes above the fluvial-aeolian plane of Záhorské pláňavy with a mosaic of river terraces, wetland depressions and sand dunes in the west and the Podmalokarpatská zníženina subsided area (depression under the Little Carpathians) with a peat bogs in several depressions in the east. The sand dunes often lie directly above the impermeable neogene layers of the Vienna Basin and dry areas at the top of sand dunes are covered by Arenosols which alternate with more moist depressions containing Cambisols, Gleysols, Podzols and Umbrisols. The soils are poor in nutrients, and pine and mixed pine-oak forests are planted here. The parent material and acid litter-fall from coniferous and broadleaf trees have induced the acid soil reaction.

3 Materials and methods

Geo-ecological research of the monitored locations was conducted as in Minár [26]; with detail topography, hydrology, lithology, pedology and vegetation investigated at the monitored sites. Groundwater table depth was determined also at the prediction-mapping soil sites, and soil profile, relief form and vegetation are described.

Detailed tacheometric survey of the terrain was performed at the Šajdíkove Humence I site and a cloud of survey points was constructed by TOPCON 105N Total station combined with GPS Leica GS20 and SK-POS correction signal for reference points. Soil pits and boreholes formed part of the survey point cloud. A digital elevation model with 1m grid-spacing was interpolated by regularised spline with tension method and default parameters included in the *v.surf.rst* module in GRASS GIS.

Geophysical research on this site contain electrical resistivity topography (ERT) and induced polarization (IP) measurements. The 2D ERT line was collected using an ARES instrument (GF Instruments Inc.). The survey line was 55 m long (see Figure 3) and conducted with a Wenner-ß electrode array with 1m electrode spacing. 56 electrodes were used simultaneously, with alternation of two current and two potential electrodes. For post-processing and data interpretation, the RES2DINV software was applied. It generates a topographically corrected 2D resistivity model of the subsurface by inverting the data obtained from electrical imaging [27]. A robust inversion (L1 norm) was used because it is more suitable for detecting sharp linear features.

The subsurface geology occasionally contained almost homogeneous internal regions but there were sharp boundaries separating different regions. In these cases, the inversion formulation was modified so that it minimised absolute changes in model resistivity values [28], and this provided significantly better results. This process is technically referred to as the L1 norm smoothness-constrained optimisation method; and commonly known as the “blocky inversion” method.

The IP data was measured in combination with ERT current applied to the ground and switched off a few moments later, thus providing over-voltage decay. The IP effect is analogous to a leaky capacitor, reflecting the degree to which the subsurface is able to store electric charge. This occurs when an electric current passes through rock or soil and the potential difference which decays over time is observed when the current is interrupted. The IP potential rate of decay depends on the rock lithology, its pore geometry and the degree of water saturation.

Soil sampling was performed down to groundwater table depth by percussion drilling in all study sites by Stitz set, and open-face auger provided umbric horizon thickness in the surrounding Šajdíkove Humence I and Ia soil pit areas.

Soil samples from the Šajdíkove Humence I and Ia and Šajdíkove Humence II soil pits were analysed by standard analytical procedures [29]. Soil reaction was determined by a glass electrode in a 1:5 volume fraction suspension of soil in water, and the cation exchange capacity and sum of exchangeable bases were established by 1M NH_4OAc at pH 7. Total carbon and nitrogen was measured by EuroVector Euro EA 3000 EA-IRMS Element Analyser. The sand colour criteria for determining groundwater-affected soils were insufficient, so the alpha-dipyridyl test was used for field identification of reducing conditions and Mn concentrations when gleyic properties were recognised by 10% H_2O_2 solution.

Soil samples for radiocarbon dating were taken twice from the bottom of the Šajdíkove Humence I topsoil layer at 40-50cm depth. Samples were soaked in distilled water and 3% H_2O_2 solution for 24 hours. Extraction of biological remains and charcoal fragments was performed using standard flotation and wet-sieving procedures with 0.25mm mesh sieve, and the charcoal fragment age was determined by radiocarbon dating. The carbon dioxide from combusted samples was catalytically converted to graphite using Vogel *et al.*’s procedure [30]. Graphite ^{14}C:^{13}C ratios were measured by CAIS 0.5 MeV accelerator mass spectrometer (AMS) and compared to the Oxalic Acid I ratio (NBS SRM 4990). The sample ^{13}C:^{12}C ratios were measured separately using a stable isotope ratio mass spectrometer (IRMS) and expressed as $\delta^{13}C$ with respect to Pee Dee Belemnite (PDB). The quoted uncalibrated dates were given in radiocarbon years before 1950 (years BP), using the 5,568 year ^{14}C half-life

Research 15m x 15m plots were established and phytocoenological relevés were performed according to the Zürich-Montpellier school and complemented by the Braun-Blanquet abundance scale.

4 Environment properties and Umbrisol mapping

Umbrisols in the Borská lowland were initially documented in the northern part of the lowland by Dlapa *et al.* [24], where an Umbrisol area formed in the shallow depression under a 75-year-old open *Pinus sylvestris* forest with dense undergrowth of *Molinia* grasses. *Molinia ceraluea* agg. [31] are the prevailing grasses in association *Molinio arundinaceae-Quercetum* Samek1962 which is an autochthonous stand in wet acidophilous oak forests. The depression is surrounded in the north-west by a sand dune with a steep slope and the terrain rises slightly to

Table 1: Chemical qualities of soils.

Locality	Longitude Latitude Altitude (m a.s.l.)	Name of soil	Index of horizon	Depth of layer (cm)	pH H_2O	Soil coloid capacity		SOC (%)	N_{tot} (%)	C_{tot}:N_{tot}
						CEC (cmolc kg^{-1})	BS (%)			
Šajdíkove Humence I	N 48.6360°		Ah_1	25	3.9	108	1.5	8.12	0.514	15.8
	E 17.2926°		Ah_1	50	4.1	57	0.4	5.52	0.409	13.5
	212,95		C_1	75	4.5	5	0.1	0.04		
			C_1	100	4.6	7	0.1	0.04		
Šajdíkove Humence Ia	N 48.6356°	Umbrisol	Ah_1	20	4.2	98	1.7	11.8	0.817	14.5
	E 17.2921°	(Arenic)	Ah_1	40	4.1	49	0.6	3.75	0.293	12.8
	213,1		C_1	75	4.4	6	0.1	0.09		
			C_1	100	4.3	8	0.1	0.08		
Šajdíkove Humence II	N 48.6362°		Ah_1	25	3,8	172	1.3	10.6	0.727	14.6
	E 17.2934°		Ah_1	45	3.7	86	0.3	5.96	0.469	12.8
	214		C_1	75	4.3	7	0.0	0.13		
			C_1	100	4.4	11	0.0	0.11		

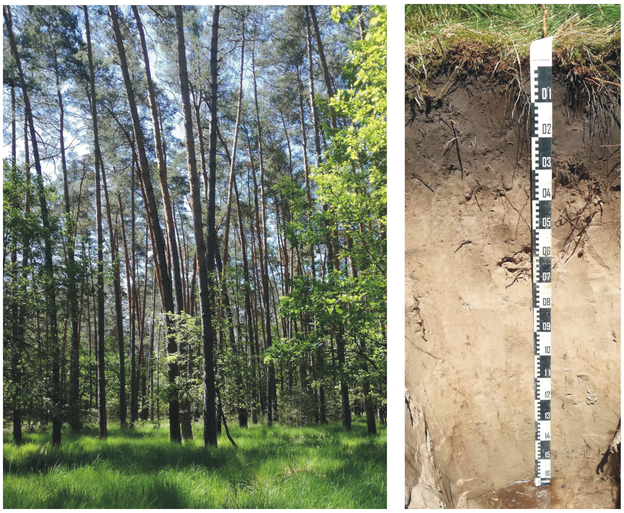
CEC = cation exchange capacity, BS = base saturation, SOC = soil organic carbon, N_{tot} = total nitrogen, C_{tot} = total carbon.

Table 2: Physical qualities of soils.

Locality	Name of soil	Index of horizon	Depth of layer (cm)	Munsell colour		Texture (%)			
				dry earth	moist earth	Clay	Silt	Sand	0.05–0.3mm
Šajdíkove Humence I		Ah_1	20	10YR2/2	10YR2/2	0.84	19.71	79.45	
		Ah_2	50	10YR2/2	10YR2/2	0.50	10.73	88.77	
		C_1	75	10YR6/2	10YR5/3	0.11	0.36	99.53	85.8
		C_2	100	10YR6/2	10YR5/3	0.37	0.18	99.45	84.7
Šajdíkove Humence Ia	Umbrisol (Arenic)	Ah_1	20	10YR2/2	10YR3/1	0.30	22.88	76.82	
		Ah_2	40	10YR2/2	10YR2/2	0.50	10.73	88.77	
		C_1	75	10YR6/2	10YR5/3	0.11	0.36	99.53	83.6
		C_2	100	10YR6/2	10YR5/3	0.37	0.18	99.45	80.7
Šajdíkove Humence II		Ah_1	20	10YR2/2	10YR3/1	0.30	22.88	76.82	
		Ah_2	45	10YR2/2	10YR3/1	1.42	12.02	86.56	
		C_1	75	10YR6/2	10YR5/3	0.25	0.19	99.56	87.1
		C_2	100	10YR6/2	10YR5/3	0.01	0.21	99.78	87.2

the southeast from its edge. The Umbrisol area is sharply bound by a sand-dune foothill and the humus-rich surface layer thickness reduces sharply behind this foothill in an uphill direction. While topsoil thickness does not change significantly to the east, its colour becomes lighter with increasing altitude until it no longer fulfils umbric horizon diagnostic criteria. The lighter colour of the adjacent Arenosols is due to decreased SOC content and the edge of the *Molinia* grass stand, which is occasionally connected to moss carpets, forms the Umbrisol border line.

The mentioned depression with the Šajdíkove Humence I and Ia soil pits borders a smaller depression to the northeast where the Šajdíkove Humence II soil pit was excavated. This depression has a 40-year-old closed canopy *Quercus robur* forest without continuous undergrowth. The diagnostic and other properties of the three



(a) Soil profile of Šajdíkove Humence Ia soil pit and *Pinus sylvestris* forest at the site.

(b) Soil profile of Šajdíkove Humence II soil pit and *Quercus robur* forest at the site.
Photos: Drahovská D.

Figure 1: Soil profiles.

representative arenic Umbrisols at the Šajdíkove Humence I and II depressions are listed in Tables 1 and 2. All have almost 50cm thick dark umbric horizons which sharply transit to a layer of light quartz eolian sand parent-material. Šajdikove Humence Ia and Šajdíkove Humence II soil pits are depicted in Figure 1.

Thickness of the umbric horizon at the bottom of the Šajdíkove Humence I depression (< 213.5 m a.s.l.) does not markedly depend on altitude (Figure 2). While its thickness in a neighborhood of a depression point reaches or exceeds 50cm, a 40-50cm thick surface horizon is located on almost the entire bottom of the depression, and differences

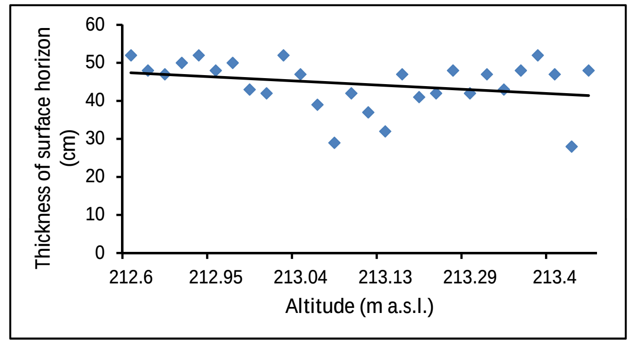


Figure 2: Dependence of surface horizon thickness on altitude, Šajdíkove Humence I site.

in altitude of particular microforms often exceed 50cm at the depression base (Figure 3). Figure 4 highlights that almost 48% of soil pits and boreholes with more than 40cm surface horizon thick are situated in micro-areas with positive plan curvature values; plan curvature is positive in ridge areas and negative in valley areas.

Determination of the groundwater table depth at the Šajdíkove Humence I and II sites was performed on 14 October 2014. Geophysical measurement and additional boreholes (percussion drilling set) showed that the groundwater table depth fluctuated approximately 1.5m in Umbrisol areas. Verification boreholes enabled determination of groundwater depth in the 2015, 2016 and 2017 summers, and they confirmed relatively stable groundwater table depth at these localities with no significant deviations from the 1.5m depth. Both localities are situated sufficiently high that permanent rivers have no effect on groundwater table height. The nearest groundwater level monitoring borehole is No. 99 in the Slovak Hydrometeorological Institute network, and this is situated close to the Bahnostream, 2.5 km north-west of the Šajdíkove Humence I soil pit at 205.18 m a.s.l. (WGS84: 48°38′37.4″N, 17°15′43.1″E). The maximum groundwater level differences recorded here were; 41cm in 2014, 28cm in 2015 and 36cm by 26 October 2016.

The chargeability model in Figure 5a depicts a 35-50cm thick surface layer. The IP results revealed a thin layer with chargeability value over12 m V/V for the umbric horizon of soil material with higher SOC content, and a thick layer of aeolian quartz sands below this layer. High carbon content, fine-grained soil fractions and sharp transformation of the layer to dry non-polarised aeolian quartz sands enabled the surface horizon to be distinguished by IP.

Changes in electrical resistivity in the transect provided modelling of the lithological composition, structure, lateral distribution and thickness of the soil horizons. Changes in porosity and water content hydrogeological pa-

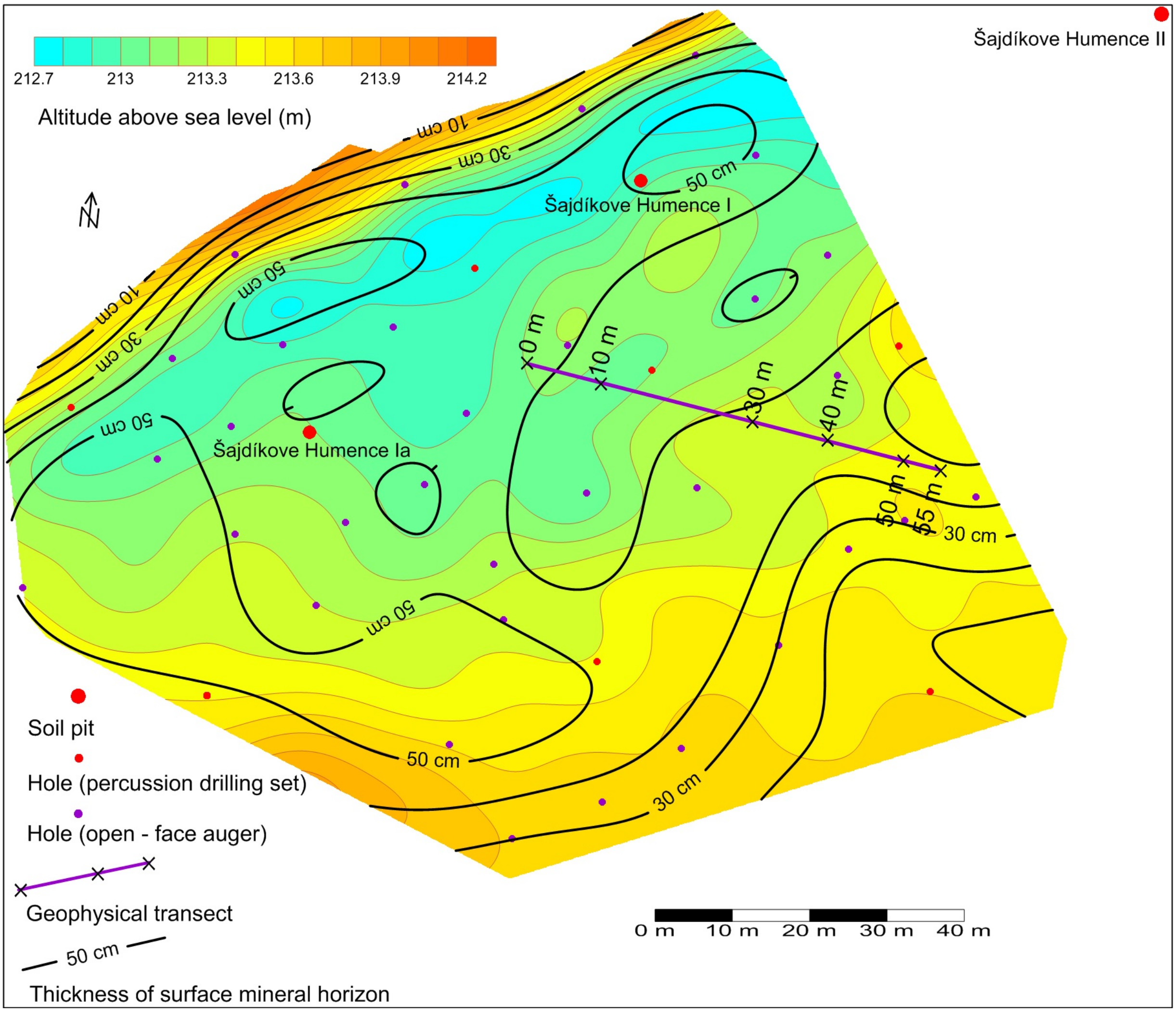


Figure 3: Thickness of dark surface mineral horizon in inter-dune depression at the Šajdíkove Humence I site.

rameters were then determined from the results. The resistivity model in Figure 5b shows the following horizontal layer distribution; the first layer is thin with resistivity ranging between 1800 and 3000 $\Omega\cdot$m and the second layer, present up to 1.5m depth, has high resistivity above 4000 $\Omega\cdot$m. Soil sampling proved that the second and third layers have similar petrophysical composition, and a resistivity decrease recorded in the third layer is explained solely by its high water content.

The chargeability, resistivity model and field soil-sampling enabled construction of lithology model (Figure 5c) which clearly corresponds to the Šajdíkove Humence I soil pit. The first border line at 0.4 to 0.5m depth on that figure corresponds to the umbric horizon interface and the second at 1.4 to 1.5m marks the top of the aquifer.

The capillary height-rise is approximately 100cm in medium-grained sand with 0.3mm average grain diameter and 0.015mm average pore radius of the soil matrix [32]. The last column in Table 2 shows that the aeolian sands have average grain diameter under 0.3mm. Although expected average pore size is over 0.015mm, the capillary rise at the Šajdíkove Humence I site encourages growth of deep-rooted grasses.

The measurements and analyses enabled specification of suitable conditions for Umbrisol formation in the Borská lowland. In addition to aeolian quartz sands, the Umbrisol areas have a shallow groundwater table (< 1.5m) with great potential for *Molinia* grass growth. These conditions are often present in inter-dune depressions, and our results provided proxies for predictive Umbrisol mapping of the entire Borská lowland (Figure 6 and Appendix, Table A1). Mapping was based on selection of 36 inter-dune depressions from the topographic map and this demonstrated the following Umbrisol occurrences at 18 sites:

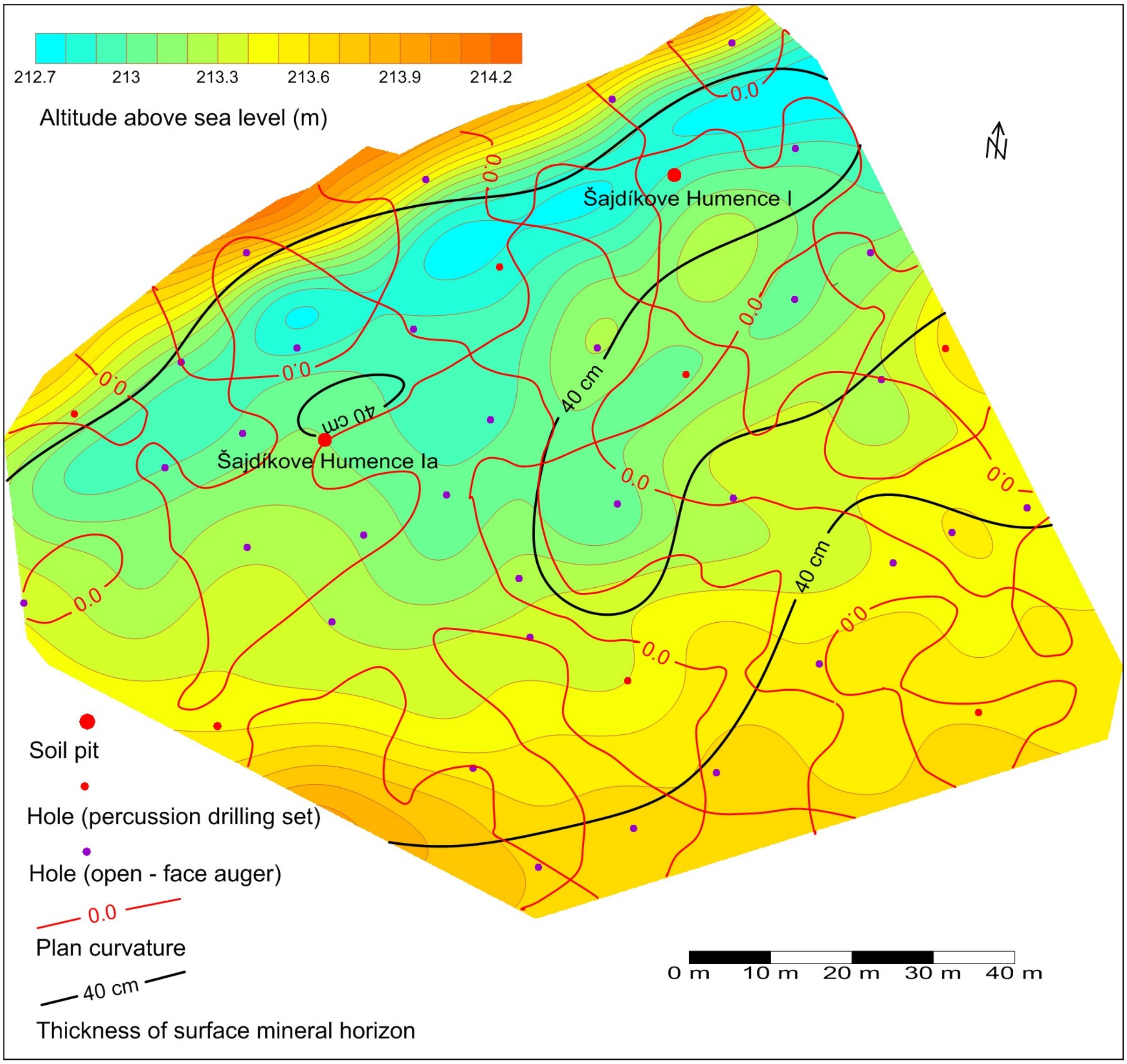


Figure 4: Plan curvature in inter-dune depression at the Šajdíkove Humence I site.

Haplic Umbrisol was classified at 6 sites; Gleyic Umbrisol at 10 sites and Cambic Umbrisols were present at the remaining 2 sites. Soils having umbric principal qualifier were also clasified (Umbric Gleysol at 8 sites and Umbric Podzol at 2 sites); and all localities with Umbrisols and soils having umbric principal qualifier are among the 33 sites with *Molinia* grass growth. Sites 35 and 36 listed on Appendix Table A1 contain two Arenosols under *Molinia* grass with a 15cm thick surface horizon which is equally dark and not base-saturated. Although these soils are not climax soils, they may transform to Umbrisols in the future. While research proved that *Molinia* grass presence is a reliable indicator of shallow groundwater table (< 1.5m), it cannot be used as sufficient indicator of Umbrisol occurrence. For example, the Šajdíkove Humence II site has oak forest without undergrowth.

4.1 Soil evolution time

The 50cm surface horizon thickness of the Šajdíkove Humence I soil pit and its ^{14}C age determination of approximately 2,000 years enable estimation of 1cm thick horizon layer forming in 40 years. This formation is more than twice as rapid as Dümig *et al*'s. estimation [33]. These authors investigated an Umbrisols under unmanaged grasslands in the southern Brazilian highland. Soil samples were taken from the same depth and specified the age using the same method. Rapid formation of the surface hori-

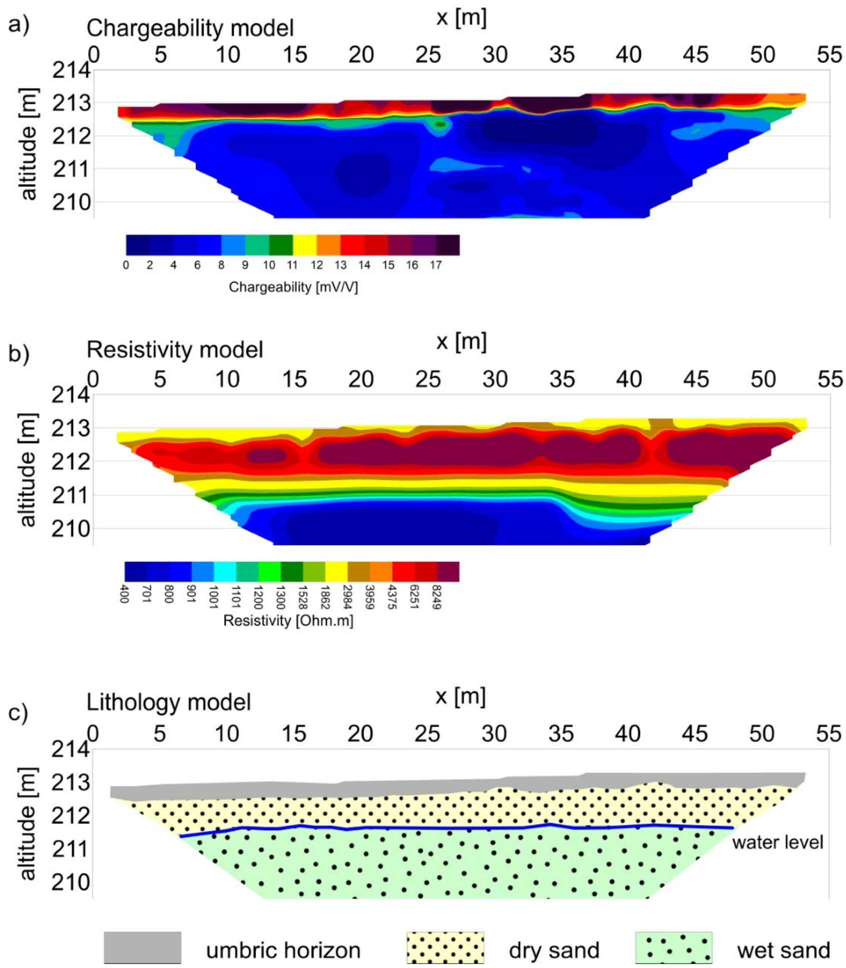


Figure 5: Results of geophysical measurements at Šajdíkove Humence I site.

zon of Šajdíkove Humence I Umbrisol generally depends on a continuous supply of material from adjacent dune slopes which are less rich in soil organic carbon (SOC), and this assumption is supported by the higher SOC content in Dümig's Umbrisols. Umbric horizons on mountain slopes can also develop more rapidly. Examples include the Cambic Umbrisols from micaschists and under the *Larix decidua*/*Picea abies* forest in the Val di Sole (Alps) at 1,621 and 1,630 m a.s.l., respectively [12]. One possible explanation is the accumulation of flushed material in concave parts of the slopes, and it is therefore unfortunate no curvature data is included in that paper.

The values of C:N ratio in the last column of Table 1 highlight the positive differences between the upper and lower half of any humus horizon, and these indicate a gradual increase in humus horizon thickness and relatively rapid soil organic matter decomposition. Bedrna *et al.* [23] record that although acid umbric horizons rich in organic matter are the poorest for micro-organism abundance, they have quite diverse microscopic fungi composition and the fastest cellulose decomposition.

5 Comparison of critical conditions for Umbrisol and Podzol formation in mountain and lowland regions

Pelíšek [34] first described a soil vertical zone formed from soils morphologically related to Umbrisols in the southern granite slopes of the Slovak Western Carpathian High Tatra Mts. This author distinguished a zone of cocoa-brown and black-grey mountain turf soils above the podzol zone. Early Slovak pedologists recognised that Alpine rankers occur above the vertical podzol zone [35, 36]. Although this zone is considered a mixed zone of Umbrisols and Leptosols, the Reference Soil Group of Umbrisols was not in-

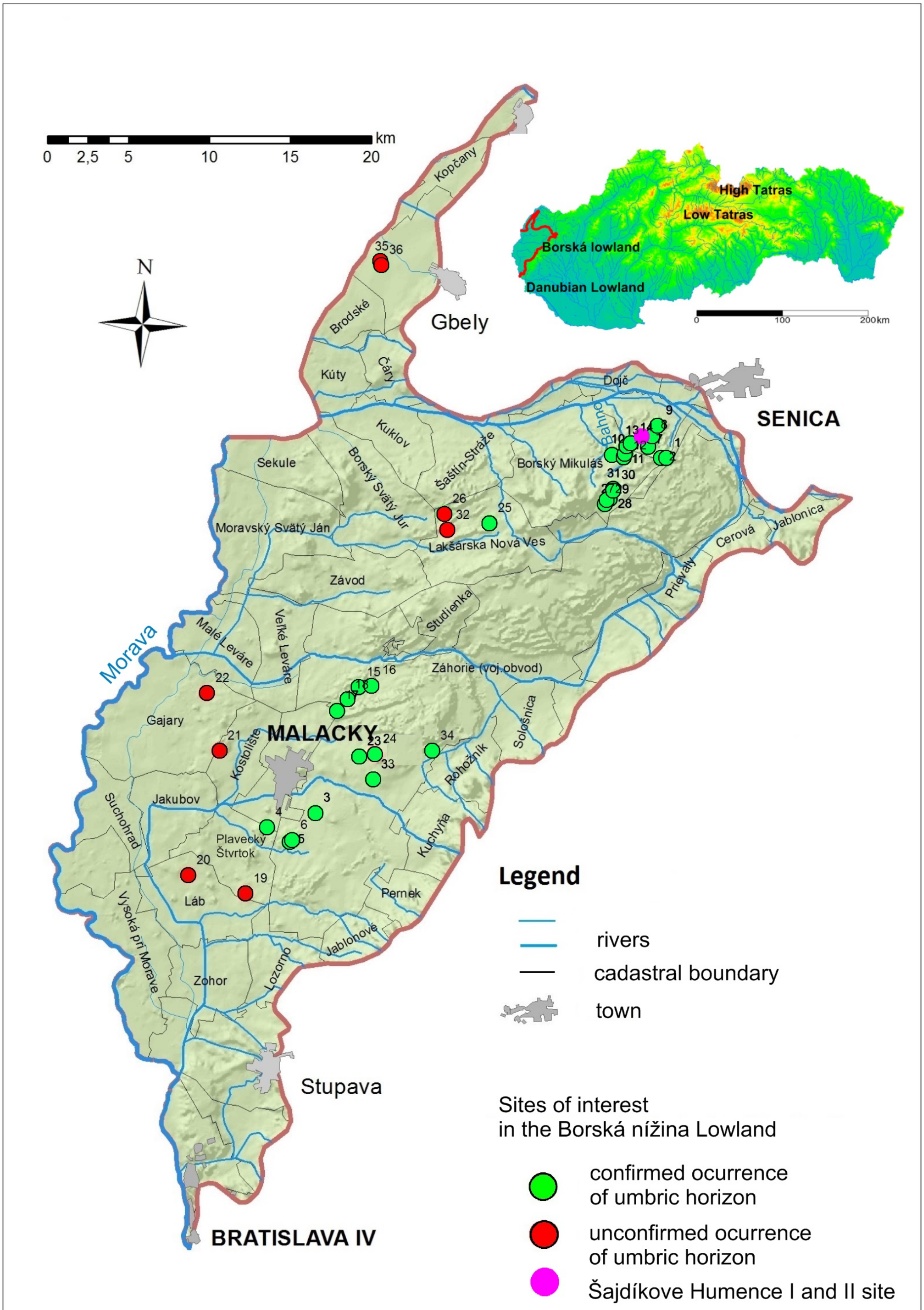


Figure 6: Occurrence of Umbrisols and other soils with umbric horizon in the Borská lowland.

cluded in the Slovak soil classification system at that time. While the “Ranker” term currently refers to lithomorphic A/C soils with varying humus horizon thickness originating from weathered silicate rocks, this soil classification unit is very broad. For example, correlation of German and WRB terms reveals that the German Ranker classification includes almost all Leptosols, Leptic Umbrisols, Cambrisols and Phaeozems [37].

Stanila and Dumitru [38] report that in the Southern Carpathians umbrisol zone lies above the podzol zone. Bedrna [39] states that a separate umbrisol zone exists between the podzol and leptosol zones in the Western Carpathians. This is supported by the occurrence of soils with an umbric horizon above the podzolised soil zone not only in the Romanian and Slovak high mountains [40], but also globally [41, 42].

Intense weathering of soil matter and translocation of its products to lower parts of the solum occurs under a cold montane closed coniferous forest. Humus accumulates in soils under open coniferous forest and alpine and sub-alpine grasslands. This is supported by the higher production of better quality organic matter, and more favourable microclimatic conditions during spring and summer, especially high ground-level air and topsoil temperatures, result in rapid formation of biomass from grasses and herbs [36]. The weathering processes decelerate more rapidly in alpine and sub-alpine grasslands than in montane coniferous forest because of the buffering capacity of a higher amount of better humus.

The Umbric Podzols in the predicted Borská lowland soil mapping are located at the bottoms of a multiple and deep depression 1km southeast of the Šajdíkove Humence I site (sites 1 and 2 on Figure 6 and in Appendix, Table A1). The depths to groundwater tables range from1.4m at site 1 to 1.0m at site 2, and both sites contain *Molinia* grasses. The extensive inter-dune depression fills with water during rainfall events, and this water accumulates in a higher water column around the lowest sub-depression points and results in longer infiltration throughout the entire solum. Lower soil temperature is related to the shallow groundwater table, and we therefore assume that subsequent soil-forming processes lead to umbric horizon development accompanied by podzolisation.

Very acidic parent material, vegetation cover and sufficient water are the major factors required for umbrisol and podzol development in both mountain and lowland areas. While sufficient water available for grasses or herbs and lower soil temperature in lowland is affected by groundwater table lying close to the ground surface, the cold montane coniferous forest and alpine environments have abundant rainfall and lower temperatures their entire area and the podzolisation process is therefore intensified.

6 Conclusion

Specific geo-ecological conditions in the central part of Borská lowland, such as acidic aeolian sands and pine-oak forests, have determined the evolution of Umbrisols in this region. Soil formation in inter-dune micro-depressions is often affected by groundwater, and unique Umbrisols are frequently found in inter-dune depressions with shallow groundwater table (< 1.5m). 1.5m depth is a transformation interface from Umbrisols to Arenosols. The properties of aeolian sands and colluvial materials flushed from the surrounding dune slopes on the bottom of inter-dune depressions induce water capillary rise to the grass roots zone during dry periods, thus providing ideal conditions for greater production of soil organic matter and consequent humification. Contrasting to Umbrisols in the mountains which fall within the altitudinal zonated soils with higher precipitation and lower temperature, the Umbrisols in the Borská lowland can be classified as intrazonal soils.

The geological and pedological settings in the Borská lowland provide favourable conditions for employing geophysical methods in detailed soil mapping, and ERT and IP measurements is especially efficient in identifying aquifers and umbric horizon thickness in the sand layers. The umbric horizon rich in SOC and the following non-water and water-sand layer are so distinct that they create a sharp interfaces between materials with different electrical properties.

In summary, very similar natural conditions to those in the Borská lowland can be expected in the majority of aeolian quartz sand outcrops in Central and Eastern Europe. An appropriate example in close proximity to the Borská lowland is the Váte Písky site near Bzenec in the Czech Republic. It is a perfectly legitimate assumption that this site also contains Umbrisols under *Molinia* grasses, and that the geophysical techniques employed in our research will prove effective in detailed soil mapping them.

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Appendix

Table A1: Environmental conditions at the inter-dune depressions.

No. of soil	Locality	Longitude Latitude Altitude	Name of soil	Depth of ground-water	Tree etage	Cover	Sub-canopy	Cover
1	Šajdíkove Humnece, Hlinený vršok I	N 48.63278° E 17.31261° 220 m a.s.l.	Umbric Podzol	140cm	*Pinus sylvestris* *Quercus petraea*	75%	*Molinia ceraluea* agg.	15%
2	Šajdíkove Humnece, Hlinený vršok II	N 48.63222° E 17.3098° 221 m a.s.l.	Umbric Gleyic Podzol	100cm	*Pinus sylvestris* *Quercus petraea*	75%	*Molinia ceraluea* agg.	15%
3	Malacky, Jablonovská cesta	N 48.41686° E 17.04879° 180 m a.s.l	Gleyic Umbrisol	80cm	*Pinus sylvestris* *Alnus glutinosa*	75%	*Molinia ceraluea* agg.	50%
4	Malacky, Syslí borník	N 48.40695° E 17.01165° 162 m a.s.l	Umbric Gleysol	70cm	*Pinus sylvestris* *Quercus petraea*	40%	*Molinia ceraluea* agg.	50%
5	Malacky, Vojenský les I	N 48.39971° E 17.03111° 174 m a.s.l	Umbric Gleysol	70cm	*Pinus sylvestris* *Quercus petraea* *Alnus glutinoza*	55%	*Molinia ceraluea* agg. *Juncus inflexus*	10%
6	Malacky, Vojenský les II	N 48.40082° E 17.03312° 175 m a.s.l	Cambic Umbrisol	120cm	*Pinus sylvestris* *Quercus petraea*	30%	*Molinia ceraluea* agg.	50%
7	Šajdíkove Humence, Šachorka I	N 48.63692° E 17.29448° 175 m a.s.l	Haplic Umbrisol	120cm	*Pinus sylvestris* *Quercus petraea*	75%	*Molinia ceraluea* agg.	60%
8	Šajdíkove Humence, Šachorka II	N 48.644° E 17.297° 200 m a.s.l	Gleyic Umbrisol	80cm	*Pinus sylvestris*	55%	*Molinia ceraluea* agg.	40%
9	Šajdíkove Humence, Šachorka III	N 48.6493° E 17.30067° 204 m a.s.l	Umbric Gleysol	70cm	*Pinus sylvestris* *Quercus petraea* *Quercus robur*	55%	*Molinia ceraluea* agg.	75%

No. of soil	Locality	Longitude Latitude Altitude	Name of soil	Depth of ground-water	Tree etage	Cover	Sub-canopy	Cover
10	Borský Mikuláš, Masárka	N 48.63152° E 17.26726° 210 m a.s.l	Gleyic Umbrisol	80cm	*Pinus sylvestris* *Quercus petraea* *Betula pendula*	15%	*Molinia ceraluea* agg.	75%
11	Borský Mikuláš, Pri obrázku I	N 48.63052° E 17.27715° 210 m a.s.l	Haplic Umbrisol	130cm	*Pinus sylvestris* *Quercus petraea* *Betula pendula*	25%	*Molinia ceraluea* agg. *Bryophyta*	15%
12	Borský Mikuláš, Pod Hlavinou	N 48.63721° E 17.27787° 212 m a.s.l	Gleyic Umbrisol	130cm	*Pinus sylvestris* *Quercus petraea* *Betula pubescens*	25%	*Molinia ceraluea* agg. *Dryopteris spinulosa* *Bryophyta*	15%
13	Borský Mikuláš, Nad Hlavinou	N 48.63721° E 17.27787° 210 m a.s.l	Gleyic Umbrisol	110cm	*Pinus sylvestris* *Quercus petraea* *Betula pubescens*	25%	*Molinia ceraluea* agg. *Dryopteris spinulosa* *Bryophyta*	20%
14	Borský Mikuláš, Pri obrázku II	N 48.63902° E 17.28229° 210 m a.s.l	Haplic Umbrisol	130cm	*Pinus sylvestris* *Quercus petraea*	30%	*Molinia ceraluea* agg. *Dryopteris spinulosa* *Bryophyta* *Caluna vulgaris*	25%
15	Studienka, Červený kríž I	N 48.48903° E 17.07526° 179 m a.s.l	Gleyic Umbrisol	80cm	*Pinus sylvestris* *Quercus petraea* *Betula pubescens*	30%	*Molinia ceraluea* agg. *Bryophyta*	30%
16	Studienka, Červený kríž II	N 48.49294° E 17.0831° 172 m a.s.l	Gleyic Umbrisol	80cm	*Pinus sylvestris* *Quercus petraea*	30%	*Molinia ceraluea* agg. *Bryophyta*	30%
17	Studienka, Červený kríž III	N 48.47449° E 17.05969° 176 m a.s.l	Gleyic Umbrisol	90cm	*Pinus sylvestris* *Quercus petraea*	30%	*Molinia ceraluea* agg. *Bryophyta*	60%
18	Studienka, Červený kríž IV	N 48.48149° E 17.0713° 182 m a.s.l	Umbric Gleysol	70cm	*Pinus sylvestris* *Quercus petraea*	30%	*Molinia ceraluea* agg. *Bryophyta*	30%
19	Plavecký Štvrtok	N 48.36865° E 16.99847° 156 m a.s.l	Gleyic Chernozem	150cm	*Pinus sylvestris*	30%	*Molinia ceraluea* agg.	1%
20	Láb	N 48.37555° E 16.9498° 154 m a.s.l	Arenosol	200cm	*Pinus sylvestris*	75%	Without plants	

No. of soil	Locality	Longitude Latitude Altitude	Name of soil	Depth of ground-water	Tree etage	Cover	Sub-canopy	Cover
21	Kostolište	N 48.44614° E 16.96492° 154 m a.s.l	Arenosol	200cm	*Pinus sylvestris*	40%	*Rubus idaeus* *Bryophyta*	30%
22	Gajary	N 48.47695° E 16.94965° 150 m a.s.l	Arenosol	200cm	*Pinus sylvestris* *Quercus petraea*	30%	*Rubus idaeus* *Bryophyta*	20%
23	Rohožník-Rohožník route I	N 48.45063° E 17.08172° 190 m a.s.l	Haplic Umbrisol	130cm	*Pinus sylvestris* *Quercus petraea*	30%	*Molinia ceraluea* agg. *Bryophyta*	30%
24	Rohožník-Rohožník route II	N 48.45276° E 17.09448° 198 m a.s.l	Haplic Umbrisol	120cm	*Pinus sylvestris* *Quercus petraea*	40%	*Molinia ceraluea* agg. *Bryophyta*	30%
25	Lakšárska Nová Ves, Kobyliarka I	N 48.58705° E 17.17072° 210 m a.s.l	Cambic Umbrisol	120cm	*Pinus sylvestris* *Quercus petraea*	55%	*Molinia ceraluea* agg. *Bryophyta*	30%
26	Lakšárska Nová Ves, Kobyliarka II	N 48.58938° E 17.13195° 186 m a.s.l	Cambisol	150cm	*Pinus sylvestris* *Quercus petraea*	55%	*Molinia ceraluea* agg. *Bryophyta*	30%
27	Bílkove Humence I	N 48.60371° E 17.26494° 230 m a.s.l	Gleyic Umbrisol	100cm	*Pinus sylvestris* *Quercus petraea* *Betula pubescens*	55%	*Molinia ceraluea* agg. *Bryophyta*	50%
28	Bílkove Humence II	N 48.60668° E 17.26897° 229 m a.s.l	Gleyic Umbrisol	80cm	*Pinus sylvestris* *Betula pubescens*	25%	*Molinia ceraluea* agg. *Bryophyta*	50%
29	Bílkove Humence III	N 48.60562° E 17.26679° 230 m a.s.l	Umbric Gleysol	100cm	*Pinus sylvestris* *Quercus petraea* *Betula pubescens*	65%	*Molinia ceraluea* agg. *Bryophyta*	35%
30	Bílkove Humence, Červený kríž I	N 48.61185° E 17.27111° 230 m a.s.l	Umbric Gleysol	60cm	*Pinus sylvestris*	5%	*Molinia ceraluea* agg. *Bryophyta*	35%
31	Bílkove Humence, Červený kríž II	N 48.61296° E 17.27095° 230 m a.s.l	Haplic Umbrisol	> 110 cm	*Pinus sylvestris*	15%	*Molinia ceraluea* agg. *Bryophyta*	25%

No. of soil	Locality	Longitude Latitude Altitude	Name of soil	Depth of ground-water	Tree etage	Cover	Sub-canopy	Cover
32	Šišuláky	N 48.58072° E 17.13597° 178 m a.s.l.	Gleysol	100cm	*Pinus sylvestris* *Quercus pubescens* *Betula pubescens*	30%	*Molinia ceraluea* agg. *Bryophyta*	35%
33	Malacky, Rybníky	N 48.43874° E 17.09514° 199 m a.s.l.	Umbric Gleysol	50cm	*Pinus sylvestris* *Quercus petraea* *Betula pubescens*	15%	*Molinia ceraluea* agg. *Juncus inflexus*	40%
34	Rohožník-gamekeeper's lodge	N 48.4581° E 17.14179° 184 m a.s.l.	Umbric Gleysol	40cm	*Pinus sylvestris* *Quercus petraea* *Betula pubescens*	15%	*Molinia ceraluea* agg.	35%
35	Gbely-Adamov route	N 48.7233° E 17.05799° 163 m a.s.l.	Arenosol	130cm	*Pinus sylvestris* *Quercus petraea* *Betula pubescens*	45%	*Molinia ceraluea* agg.	10%
36	Gbely-grove	N 48.7233° E 17.05799° 160 m a.s.l.	Arenosol	130cm	*Pinus sylvestris* *Quercus petraea* *Betula pubescens*	45%	*Molinia ceraluea* agg.	10%