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RELATIONS BETWEEN BIOTIC AND ABIOTIC DIVERSITY IN ABANDONED BASALT QUARRY AND ITS RELEVANCE FOR ECOLOGICAL RESTORATION (RADOBÝL HILL, NORTHERN CZECHIA)

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Abstract

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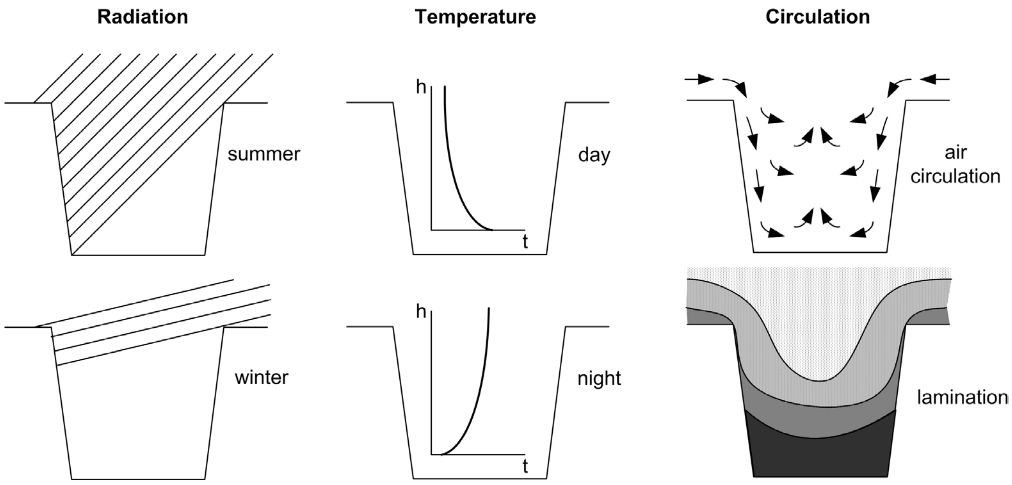
The ecological value of abandoned quarries has gained increasing scientific attention in the last few decades, resulting in a paradigm shift in restoration programs regarding the use of natural processes. The linkages between biotic and abiotic diversity, such as landform and microclimatic diversity have been analyzed only slightly, however. In this paper, we use an interdisciplinary approach that includes vegetation mapping, geomorphological mapping, microclimatic measurements and modeling to reveal the specific two-way linkages between abiotoc and biotic diversity. The present case study shows that in only 60 years landform diversity allowed the development of nine distinct biotopes with 134 identified species. At the same time, the vegetation diversity at these human-induced biotopes is of high ecological value as it displays significant similarities with natural biotopes in the region (e.g., scree slope and rock cliff biotopes). Based on the results presented, the paper aims to contribute to current restoration programs involving processes of spontaneous succession and landforming.

Keywords: quarry; biotope; vegetation patterns; landform diversity; microclimate

INTRODUCTION

Quarrying ranks among the most significant impacts of human activities caused to the environment. Although the extraction of building stone in Central Europe is usually limited to small localities in contrast to open-cast mining of fossil fuels, it has serious negative ecological impacts including landform and biotope destruction, disturbation processes caused by natural hazards (rockslides and rock falls) and increase in dust particle volume and noise level due to rock blasting and transportation, which have resulted in increasing attention being paid to both operating and abandoned quarries.

On the other hand, the positive ecological and geoscientific value of abandoned quarries has only recently gained appreciation by the scientific community. This, in turn, has resulted in a paradigm shift in restoration program toward the use of natural processes in restoration efforts, which is documented by detailed studies (e.g., Davis 1982 ed, Browning 1998, Tropek *et al.* 2010) as well as conceptual works (Bradshaw 1997, 2000, Bradshaw and Hüttl 2001). Of the ecological studies performed mainly in limestone and basalt quarries, attention has been paid to the spontaneous succession of vegetation and its determinants (Ursic *et al.* 1997, Cullen *et al.* 1998, Novák and Prach 2003), to describing and understanding the spontaneous



1: *Microclimate of operating quarries (after Loksa 2007).*

succession specific to Arthropoda assemblages (Holec *et al.* 2010), mostly spiders (e.g., Wheater *et al.* 2000, Tropek and Konvička 2008, Holec and Pokorný 2009, Košulič *et al.* 2013), butterflies (e.g., Beneš *et al.* 2003, Brown *et al.* 2011), and beetles (e.g., Nováková and Šťastná 2013) and to the evaluation of importance of abandoned quarries for nature conservation (Chuman 2007).

The attention of biologically oriented ecologists devoted to the influences that microscale abiotic (mainly landform and microclimate) diversity has on diversity of the biotic environment, however, has been rather scarce. At the same time it was indicated that understanding dynamics of abiotic diversity in abandoned quarries may have important implications for restoration management. Walton and Allington (1994), Dávid (2008) and Schor and Gray (2007) emphasized the necessity of a geomorphologic approach to landform replication in abandoned quarries to increase quarry biotope geodiversity, while Tomlinson *et al.* (2008) evaluated the analogies of certain quarry features to natural landforms. Cevizci (2015) has shown how different blasting methods may influence rock clast distribution in quarries. Furthermore, Loksa (2007) has shown significant variation in the incoming solar radiation, temperature and air circulation (Fig. 1) that may affect biotope diversity in quarries. Site-specific examples of biotope-landform links were presented by Zhang and Chu (2011) and Bétard (2013).

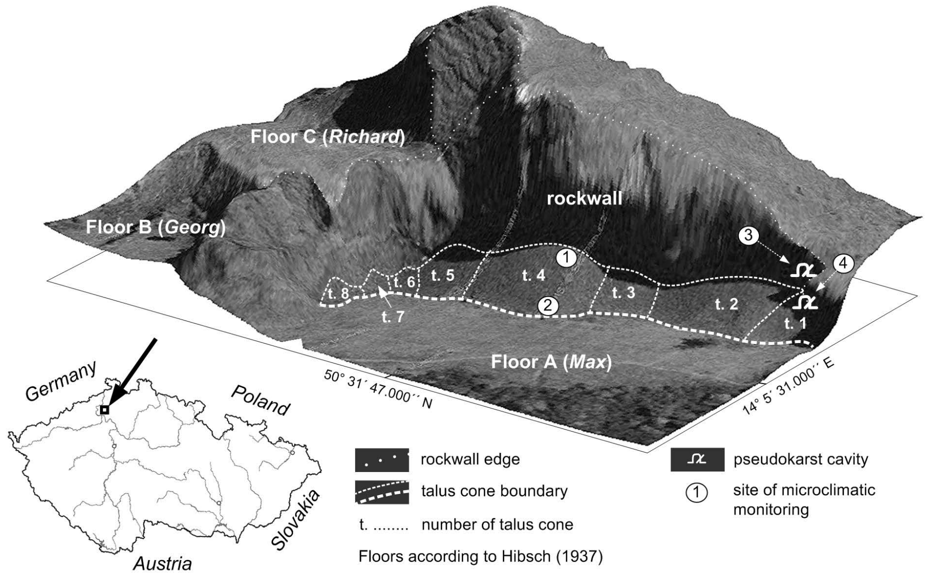
This study reports the results of a case study of Radobýl Hill in the České středohoří Mountains in North Czechia, an interdisciplinary research project devoted to the significance of the ecology of historical (abandoned) basalt quarries. It builds upon previous work, analyzing the diversity and dynamics of landforms in an abandoned basalt quarry at Radobýl Hill (Raška *et al.* 2011a). In this paper, we present the results of the final research phases, in which the attention has been paid to vegetation mapping at the level of biotopes and analyses of microclimatic variations related to landform-induced biotopes. By analyzing the linkages among the specific landforms, their microclimatic regimes and the present vegetation patterns that were developed at the study site, the study aims to contribute to current restoration programs involving processes of spontaneous succession and landforming.

MATERIALS AND METHODS

Study site

The study site is located in northwestern Czechia (Fig. 2), which is affected by long-term mining and quarrying of various raw materials (Balej *et al.* 2007). The quarrying of building stone is mainly concentrated in the neovolcanic (37–9 Ma) range of the České středohoří Mountains, an area characterized by basalts, trachytes and phonolites (Cajz 1996, 2000), which are suitable for building purposes. The study site of Radobýl Hill (399 m a.s.l.; 50° 31′ 47.00 N, 14° 05′ 33.00 E) is located in the southern rim of the mountain range. The mean annual temperature varies between 9 and 10 °C, and the total annual precipitation is 400–500 mm, ranking the region among the warmest and driest in Czechia (Czech Hydrometeorological Institute).

The quarrying of basalt at the hill resulted in the formation of three floors (etages), with rockwalls reaching more than 50 m in height, and in the formation of several fine- to coarse-grained talus cones. Furthermore, ca. eight m long cavity originating from a prehistoric deep-seated landslide (Pokorný and Vrabec 2011) and exposed by quarrying is present in the rockwall of the lowest quarry floor. This research was carried out at the lowest (and largest) floor of the abandoned quarry. The date when quarrying first began at this site cannot be determined due to the unavailability of archive sources, but the quarry began operating at least by the late 19th century, according to military maps from 1877–1880, and it ceased operation



2: *Location and DTM of the study site. (Note: Numbers in circles show the position of detailed microclimatic measurements).*

before World War II (Hibsch 1937). In 1963, the quarry was established as a natural reserve because of its geological and biological significance. Currently, it is protected under the NATURA 2000 program, and its significance was internationally confirmed when it was referred to as a comparative site in a proposal to add the famous *Giant's Causeway* in Northern Ireland to the World Heritage Site list (Anonymous 1985).

Digital terrain model and geomorphologic mapping

Field survey and solar radiation modeling were based on high-resolution digital terrain model (DTM). The elevation data have been acquired by terrestrial geodetic measurement with total station (Trimble 5603 DR200þ+) using the prismless automatic measurement mode. The measurement sites have been localized in situ using the GPS receiver (Trimble R8) in RTK (real-time kinematic) method. The final point cloud has been checked visually for outliers and then used to derive the DTM of the study site with 1 m resolution (Raška *et al.* 2011a). We then performed a large-scale geomorphological mapping on the constructed DTM to identify the main quarrying-related landforms.

Biotopes mapping

A detailed botanic field survey was carried out in May and August of 2012 and 2013. The plant taxons are listed according to the Key to the Flora of the Czech Republic (Kubát 2010 ed). Special attention has been devoted to the assignment of the identified taxons to ecological groups and to identifying the endangered taxons according to the Red List of Vascular Plants of the Czech Republic (Grulich 2012). Finally, we determined the types of mapped biotopes together with the present plant taxons. Phytosociological alliances were determined according to Chytrý (2010a ed, 2010b ed, 2013 ed). The mapped biotopes were then compared with respect to their location and extent to the present landform types and their microclimatic specifics.

Microclimatic analysis

The microclimatic analysis was carried out in two steps according to standard procedures (e.g., Yüksel 2008). First, direct temperature monitoring was performed to analyze the temperature regimes at the largest talus cone and in a cave (Fig. 2). A pair of MINIKIN dataloggers TH (EMS Brno) with a temperature sensor precision of ±0.2 °C was installed for one year (April 24, 2010–May 10, 2011; one hour measurement interval) at the upper and lower site of the largest talus cone. The elevation difference between the upper and the lower site was ca. 20 m.

Furthermore, we carried out episodic monthly measurements of maximal and minimal temperatures using two extreme mercury-alcohol thermometers (September 1, 2007–September 1, 2008) installed in pseudokarst cavity.

Second, we performed solar radiation modeling to analyze the spatial variability of incoming solar radiation during the year because some parts of the quarry were inaccessible for taking direct measurements. The modeling was realized in a GIS environment (Geographic Information Systems, ESRI ArcGIS 10), implementing the standard procedures described by Böhner and Antonić (2009). The average annual intensity of incoming solar radiation was based on azimuth and sun height data (Appendix 1) at noon on the 15th day of each month using an altitude correction for the lower quarry floor (350 m a.s.l.).

Because the main quarry rockwall is north-south oriented (i. e. with westward exposure), we also considered a possible different incoming solar radiation regime during the day. Therefore, we created a set of models for a sample date (June 30; two-hour interval) from sunrise to sunset and analyzed the daily rhythm of incoming solar radiation.

RESULTS

Landform diversity

Detailed geomorphological mapping allowed for the identification of the following landforms, which are present in the lowest floor of the quarry:

(a) Rockwall: Its height ranges from a few meters at the sides to 55 meters in its central part. The continual segment of the rockwall reaches a height of 46 m. The rockwall displays columnar jointing of basalts with vertical to subhorizontal inclination (8–70°). Large differences in inclination, together with calcified weathering in the intercolumnar joints, contributed to rockwall disintegration. This, in turn, results in frequent rock fall, which affects the grain patterns of the talus cones.

(b) Talus cones: Eight talus cones of different morphologies are present in the floor. They formed from the accumulation of rockwall clasts during and after the quarry operation. A comparison of historical and present-day photos shows the accumulation rate of ca. 1 m in 50 years. The length of the talus cones is between 7 and 33.5 m, with an average inclination of 32°. Whereas the talus cones located beneath the highest segments of the rockwall affected by rock fall and debris-flow processes display a mixed (fine- to coarse-fine) grain pattern, the marginal, smaller taluses are coarse-grained. The uppermost segments of the central talus cones have a clayey infill.

(c) Quarry floor: The quarry floor is represented by a flat surface scarcely covered by clasts, mainly in the transition (ecotone) zone of the talus cones.

(d) Radobýl cave: The cavity in the S margin of the quarry floor has formed as a result of deep-seated gravitational slope deformation during the Pleistocene and has been exposed by quarrying activity. Its length is eight meters and its width ca. 1 m. The ceiling is formed by a loess infill of the vertical joint (cf. Pokorný and Vrabec 2010).

Monitoring of thermal regime

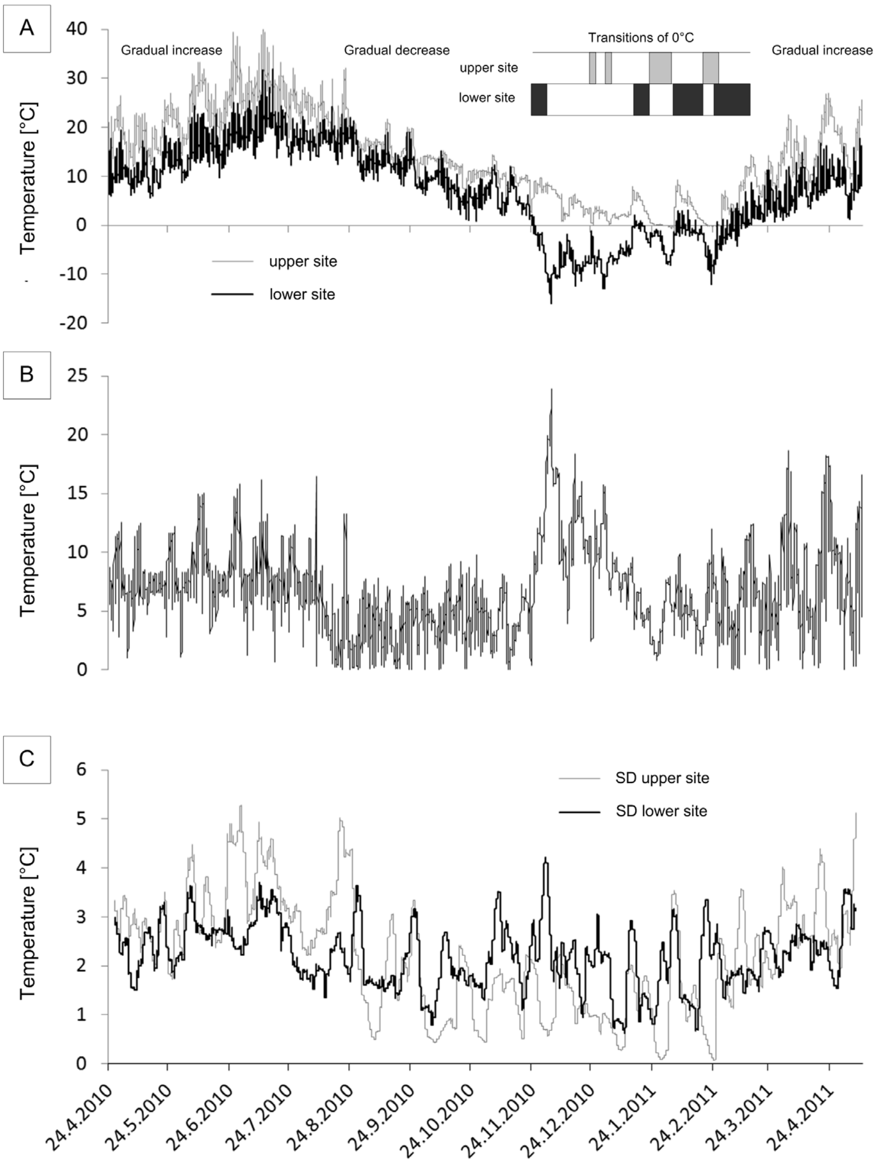
The temperature data measured at the upper and lower site of the largest talus cone in the quarry displays significant differences during the year (Tab. II). The average temperature at these sites differed by ca 7 °C, with approximately same difference during the spring to autumn and winter period. However, during the winter period, the difference of ca 6 °C has caused that the average temperature at the upper site was above the 0 °C, while the cold descending air inside the void system caused the decrease of the average temperature at the lower site to less than −3 °C. Moreover, the daily temperatures during the winter period differed by almost 25 °C, which indicates that air circulates within the open void system of the talus cone (Fig. 3, Tab. I). The standard deviation of the temperatures, which can be used as an indicator of temperature stability, was higher by ca. 1 °C during the spring to autumn period. This means the spring to autumn temperatures are more sensitive to ambient air temperature variations, which is similar to the temperature regimes of the natural scree slopes in the region (Zacharda *et al.* 2007, Raška *et al.* 2011b).

The maximal and minimal temperatures in the pseudocarst caves are shown in Fig. 4. These values, compared with our unpublished measurements from other cavities in the České středohoří Mountains, show that the caves at Radobýl differ from most of the other cavities in the area. Relatively high average annual temperatures and summer temperatures were characteristic for the inner part of the Radobýl cave.

Modeling the extent of direct radiation

Modeling of the incoming solar radiation has confirmed the highest annual incoming radiation to the southward oriented rockwall above the talus cones numbered 6, 7 and 8 and to the southward oriented segments of the largest talus cones (Fig. 5). The overall differences in the incoming solar radiation are not high, however, and the area of patches with below-average incoming solar radiation is rather small. Moreover, the effects of variations in the incoming solar radiation on the talus cone microclimate are partly modified by vegetation patterns, mainly by trees and shrubs along the lower rim of the talus cones.

A significant variation in the incoming solar radiation has been detected for the daily regime, which is caused by the generally westward orientation of the main rockwall and of the largest talus cones (Fig. 6). The general patterns show above-average incoming solar radiation in contrast to other natural sites in the region. The incoming solar radiation starts to increase significantly only four hours after sunrise, reaching its maximum between two and four p.m. This variation, along with above-average values, is assumed to predispose the site to the presence of xerothermic vegetation units (see Section 3.4).

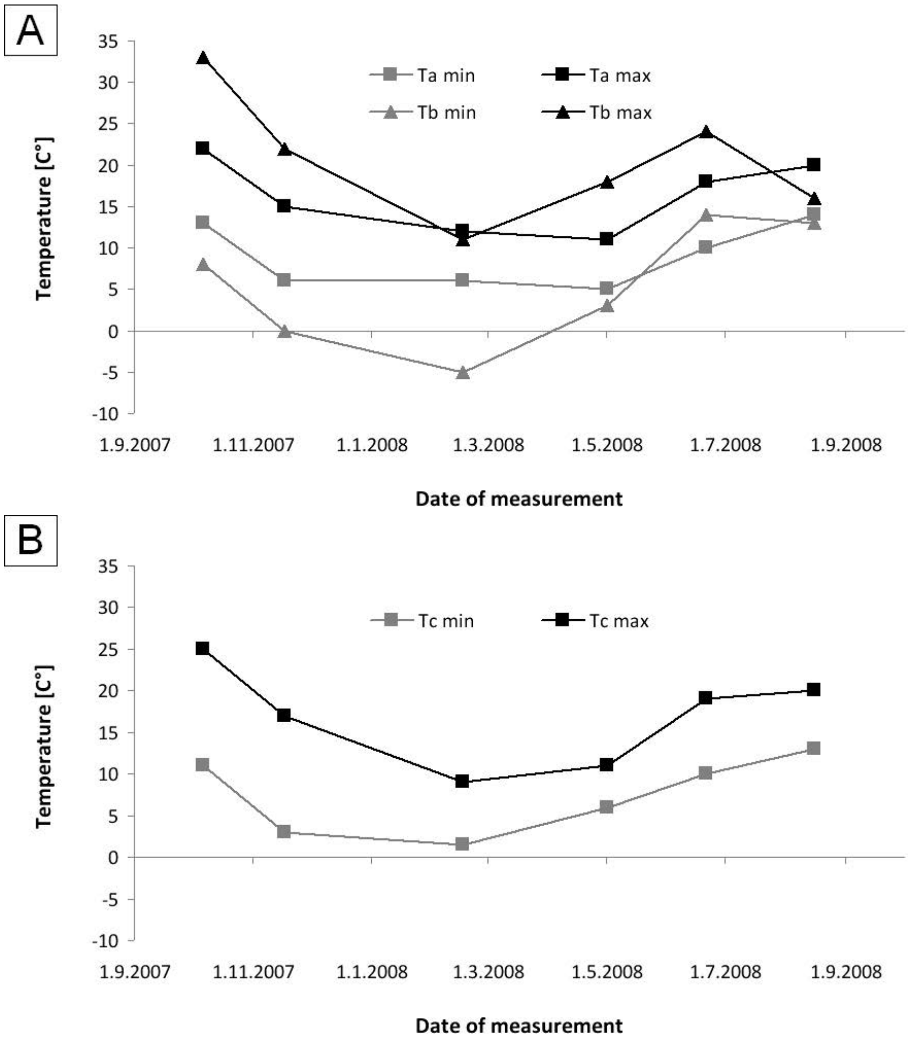


3: *Thermal regime at the talus cone number 4. A – temperature at the upper and lower site, B – differences in temperatures, C – 7-day running standard deviation for temperatures at the upper and lower site [°C].*

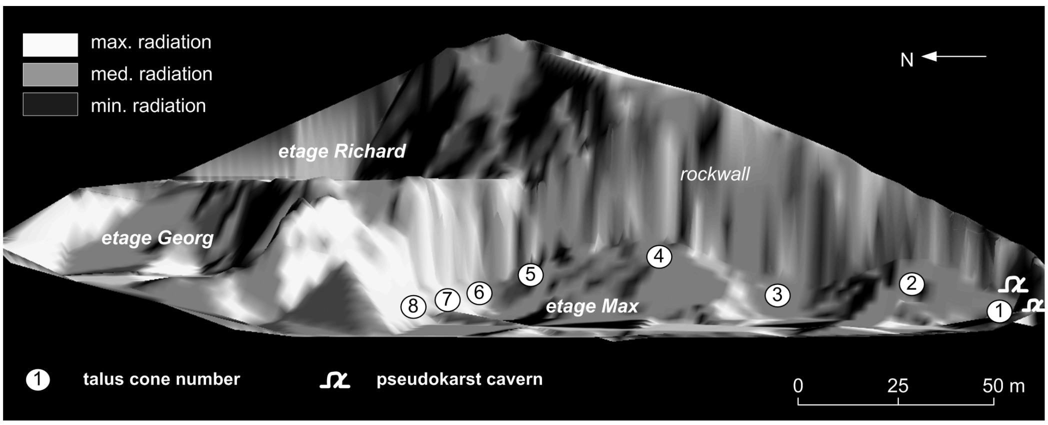
I: *Statistical characteristics of the thermal regime at the talus cone number 4.*

Indicator	upper site [°C]	lower site [°C]
av. temperature	13.70	6.94
av. temperature spring to autumn	16.86	9.99
av. temperature in winter	3.29	–3.06
s.d. temperature spring to autumn	2.45	2.31
s.d. temperature in winter	1.40	1.84
av. differences in temperatures spring to autumn	6.92	
av. differences in temperatures in winter	6.35	

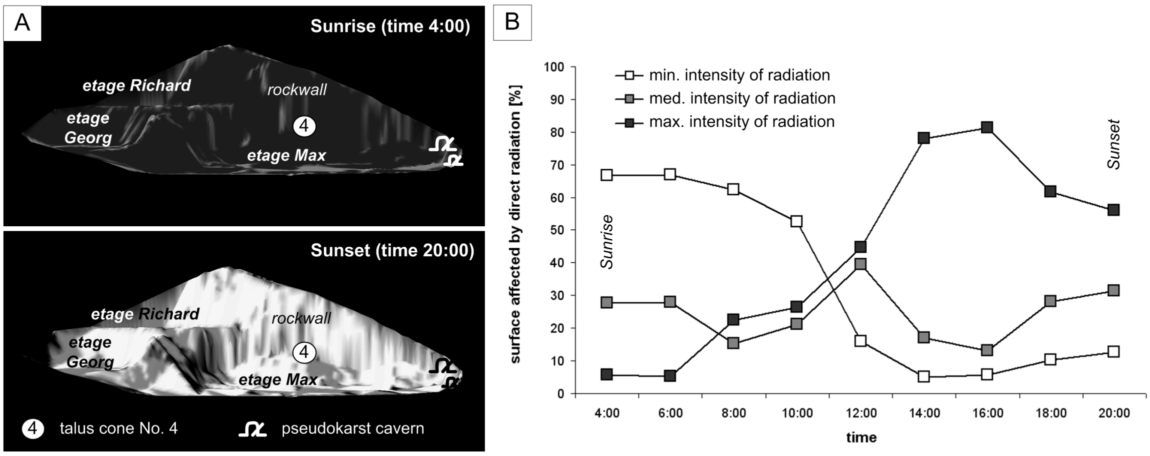
Note: SD – standard deviation, av. – average.



4: *Thermal regime in the pseudokarst caves A and B (Ta – data inside the larger pseudokarst cave, Tb – comparative data outside the cave, Tc – data inside the small pseudokarst cave).*



5: *Extent of surface affected by direct radiation – annual average.*



6: *Extent of the surface affected by direct radiation (for the June 30): A – representation in DTM for 4:00 (sunrise) and 20:00 (sunset), B – extent of the surface affected by the direct radiation during the day.*

Vegetation units

The vegetation mapping allowed us to identify nine vegetation units (biotopes A-I), which are summarized in Tab. III and described below. A simple Jaccard's similarity index was used to describe species similarity among biotopes (Tab. IV). The list of all determined plant species is shown in Appendix 2.

Biotope A includes quarry rock-outcrop communities with succulents (6110; alliance *Alysso alyssoidis-Sedion* Oberdorfer et Müller in Müller 1961). This biotope, which is small in extent, is located along the upper part of the quarry rockwall, with a slope of ca 50°, and it continues into the upper quarry floor. It is characterized by high microtopographic diversity predisposed by columnar jointing of basalts. With intensive insolation, this biotope has a patchy vegetation cover consisting of succulents (mainly *Sedum album* L. and *Sedum sexangulare* L. and some *Jovibarba globifera* (L.) J. Parnell), low xerophytic perennials (e.g., *Dianthus carthusianorum* L., *Potentilla arenaria* Borkh. and *Euphorbia cyparissias* L.), of grass (*Festuca pallens* Host), and lichens.

Biotope B includes chasmophytic vegetation of the sunny quarry face (6190; alliance Alysso-Festucion pallentis Moravec in Holub *et al.* 1967). It has a sunny rockwall with narrow joints between basalt columns and with small rock ledges (terraces). With its low volume of fine-grained soils in joints that rapidly dry out, and with the high incoming solar radiation and temperature amplitudes, this biotope has the most extreme ecological conditions of all of the mapped biotopes.

II: *Vegetation units of the lowest floor of the abandoned quarry at Radobýl Hill.*

Biotope codes	Name	Natural Habitat Type	Alliance	No. of species
A	quarry rock-outcrops communities with succulents	6110	*Alysso alyssoidis-Sedion*	20
B	chasmophytic vegetation of the sunny quarry face	6190	*Alysso-Festucion pallentis*	33
C	chasmophytic vegetation of the shaded quarry face	6220	*Asplenion septentrionalis*	22
D	xerophytic ruderal vegetation of the upper edge of the scree accumulation	–	*Dauco-carotae- Melilotion*	52
E	sporadic vegetation of the scree accumulation	8150	*Stipion calamagrostis*	15
F	xeric scrub with dominant *Populus tremula*	–	*Berberidion vulgaris*	15
G	narrow-leaved dry grassland	6210	*Festucion valesiacae*	50
H	broad-leaved dry grassland	6210	*Cirsio-Brachypodion pinnati*	49
I	tall xeric scrub	–	*Berberidion vulgaris*	23*

* – only trees and shrubs

III: *Jaccard's similarity index of species at individual biotopes.*

Biotope codes	A	B	C	D	E	F	G	H	I*
A	100.00	51.43	27.27	24.14	20.69	0.00	25.00	9.52	2.38
B		100.00	30.95	44.07	23.08	2.13	38.33	15.49	3.70
C			100.00	15.63	23.33	0.00	20.00	4.41	0.00
D				100.00	17.54	6.35	30.77	12.22	13.64
E					100.00	0.00	12.07	3.23	0.00
F						100.00	0.00	0.00	40.74
G							100.00	23.75	0.00
H								100.00	1.41
I*									100.00

The present species are resistant to significant microclimatic variations. This biotope includes species that are common for dry grasslands (*Echium vulgare* L., *Centaurea stoebe* L., *Thymus pannonicus* All., *Artemisia campestris* L., *Silene otites* (L.) Wib. and *Asperula cynanchica* L.), chasmophytes (e.g., *Asplenium septentrionale* (L.) Hoffm.), succulents (*Sedum album* and *Hylotelephium telephium* (L.) Ohba) and a few small shrubs (*Rosa* sp.). The relatively higher diversity of this community (33 species) is predisposed by three factors: (i) the mineral content of the parent material, (ii) its location in a thermophytic area, and (iii) by above-average insolation. On the other hand, vegetation is wholly absent on the quarry wall segments that lack intercolumnar joints and rock ledges.

Biotope C includes chasmophytic vegetation of the shaded quarry face (6220; alliance *Asplenion septentrionalis* Gams ex Oberdorfer 1938). This biotope, which is smaller and is found along the north-oriented part of the rockwall, is characteristic of the joint system and small ledges in contrast with biotope B. Also in contrast to biotope B, the vegetation has lower diversity (22 species) and its shading results in the presence of sciophillic species of ferns (*Asplenium ruta-muraria* L., *A. septentrionale* and *A. viride* Huds.), bryophytes (*Hypnum cupressiforme* Hedw.) and lichens (*Parmelia* sp.), which are accompanied by less abundant grasses (*Poa angustifolia* L.), succulents, and perennials (*Rumex acetosella* L. and *Hieracium sabaudum* L.).

Biotope D includes xerophytic ruderal vegetation of the upper edge of the scree accumulation (alliance *Dauco carotae-Melilotion* Görs ex Rostański et Gutte 1971). This biotope, which is the alliance located at the upper rim of the talus cones in a 0.5–3 m wide strip, is associated with a fine-grained and rapid-drying substrate that includes a small amount of humus. The fine-grained material comes from aragonitic and calcitic infill of the intercolumnar joints (Pokorný and Holec 2009). This xerothermic and thermophilic community has the highest diversity of all of the biotopes (52 species) and includes species also present in the rockwall locations, as well as ruderal species (e.g., *Urtica urens* L., *Lactuca serriola* L., *Artemisia vulgaris* L., *Senecio vulgaris* L. and *Galium aparine* L.). The share of these species is higher than in the other mapped biotopes. It also consists of nine species of woody plants (e.g., *Sambucus nigra* L., *Ulmus minor* Mill., *Juglans regia* L., *Ligustrum vulgare* L. and *Prunus spinosa* L.), succulents (*Sedum album*) and grasses (*Melica transsilvanica* Schur and *Poa bulbosa* L.).

Biotope E includes sporadic vegetation of the scree accumulation (8150, alliance Stipion calamagrostis Braun-Blanquet *et al.* 1952). This biotope, where most of the area is without vegetation, is caused by a combination of the following stresses: the presence of large boulders without fine-grained infill, the high temperature variations and disturbances caused by scree dynamics, alltogether resulting in undersaturation with water. Lichens (*Lepraria* sp.) have colonized the surface of the shadowed segments of the individual clasts of stones. Ferns (*Dryopteris filix-mas* (L.) Schott) and vascular plants (*Lactuca viminea* (L.) J. Presl et C. Presl and *Conyza canadensis* (L.) Cronquist) are present in the voids, whereas succulents (*Sedum album*) and mosses are sporadically present at small fine-grained patches. The lower rim of the scree (talus cones) is more stabilized and continues to biotope F.

Biotope F includes xeric scrub with dominant *Populus tremula* L. This biotope forms a lower rim of the talus cones and is characterized by the presence of smaller thermophile shrubs (13 species), which are associated with relatively higher soil moisture. The real abundance depends on the landscape management measures carried out by the administration of the legislatively-based Protected Landscape Area (mainly clearance of dominant *Populus tremula* to limit its expansion to the valuable biotopes of dry grasses).

Biotope G includes narrow-leaved dry grassland (6210; alliance *Festucion valesiacae* Klika 1931). The biotope is located in the northern and eastern part of the quarry floor. Dominance of the vernal aspect is caused by drying of the soil substrate during the summer months. The biotope consists of narrow-leaved grasses (mainly *Arrhenatherum elatius* (L.) J. Presl et C. Presl subsp. *elatius* and *Bromus erectus* Huds.) and geophytes (*Echium vulgare* and *Scabiosa ochroleuca* L.). Furthermore, thermophytes are abundant in this biotope (*Artemisia campestris*, *Thymus pannonicus*, *Centaurea stoebe*, *Euphorbia cyparissias*, *Potentilla arenaria*, *Eryngium campestre* L., *Dianthus carthusianorum*, *Anthyllis vulneraria* L. and *Pseudolysimachion spicatum* L. Opiz). This biotope has evolved at the secondary site, but – with its protected species – it does have a fundamental role in landscape conservation (*Stipa capillata* L., *Pulsatilla pratensis* (L.) Mill. subsp. *bohemica* Skalický, *Astragalus exscapus* L. and *Muscari tenuiflorum* Tausch). The diversity is threatened by expansion of *Calamagrostis epigejos* (L.) Roth.

Biotope H includes broad-leaved dry grassland (6210; alliance *Cirsio-Brachypodion pinnati* Hadač *et* Klika *ex* Klika 1951). It consists of the western and southern part of the quarry floor. The site is influenced by presence of a tourist path resulting in effects from walking. The biotope includes a diversity of grasses (e.g., *Bromus erectus* and *Phleum phleoides* (L.) Karsten) and herbs (*Achillea millefolium* L., *Galium verum* L., *Echium vulgare*, *Cichorium intybus* L., *Stachys recta* L., *Lotus corniculatus* L., *Hypericum perforatum* L., *Vicia angustifolia* L. and *Falcaria vulgaris* Bernh.). Its western part is influenced by the expansion of shrubs and grasses (*Arrhenatherum elatius* subsp. *elatius* and *Calamagrostis epigejos*).

Biotope I includes tall xeric scrub (alliance *Berberidion vulgaris* Braun-Blanquet ex Tüxen 1952). The biotope is represented by a diverse specter of shrubs and small trees located at the outer rim of the quarry floor. It includes thermophilic species and less abundant species connected to human settlement (*Syringa vulgaris* L. and *Symphoricarpos albus* (L.) Blake). The vascular plants are similar to those in biotope H.

DISCUSSION AND CONCLUSION

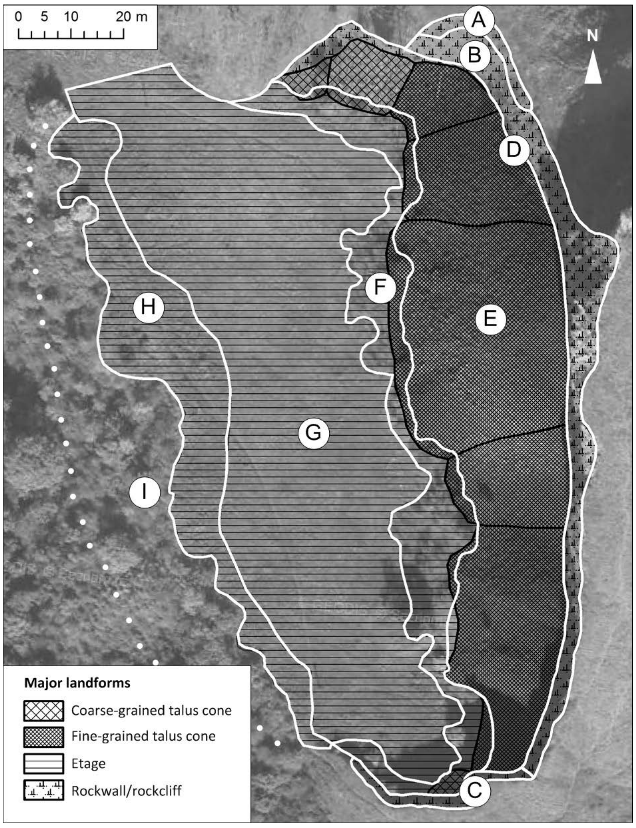
In this research, we used an interdisciplinary approach of ecology, geomorphology and microclimatology to reveal the relations between biotope diversity and human-induced landforms (abandoned basalt quarries). Recent results of bioecological studies indicate that abandoned basalt quarries may represent a significant biotope in the surrounding vegetation matrix (e.g., Novák and Prach 2003). Based upon these results, our aim was to analyze to what degree the mosaic of biotopes correspond to landform diversity to testify to the applicability of two different strategies: (i) the landforming strategy (Schor and Gray 2007) and (ii) the use of natural processes in reclamation design (Bradshaw 2000). These strategies are often presented as opposing approaches to quarry restoration, while their possible complementarity was minimally explored.

Our field survey has revealed a diversity of quarry landforms, which are developed in a very distinct manner. The vegetation mapping allowed for the identification of nine biotopes (with 134 determined plant species), one of which is a 'priority habitat type' (6110) (Chytrý 2010a ed, 2010b ed, 2013). Generally, the secondary biotopes of the quarry enabled the development of natural to semi-natural plant communities in only 60 years after the quarry ceased to operate. According to the Red List of Vascular Plants of the Czech Republic (Grulich 2012), the studied quarry floor consists of four endangered species (*Astragalus exscapus*, *Muscari tenuiflorum*, *Prunus fruticosa* Pallas, and *Pulsatilla pratensis* subsp. *bohemica*), seven vulnerable species, and thirteen potentially vulnerable species. The results of microclimatic measurement and modeling have shown that the landform diversity is clearly linked to microclimatic variability as an important ecological factor. Finally, the combination of results obtained from the vegetation and geomorphological mapping enabled the identification of the general agreement between landforms and biotopes as shown in Fig. 7. In this respect, significant variance in temperatures and incoming solar radiation at the individual landforms also resulted in distinction among the individual biotopes (Tab. IV and V). Moreover, the results from the direct temperature measurements at the largest talus cone indicate that it represents an artificial alternative for extreme biotopes of natural scree slopes with negative temperature anomalies during the year (cf. Kubát 2000 ed., Raška *et al.* 2011b; Fig. 8).

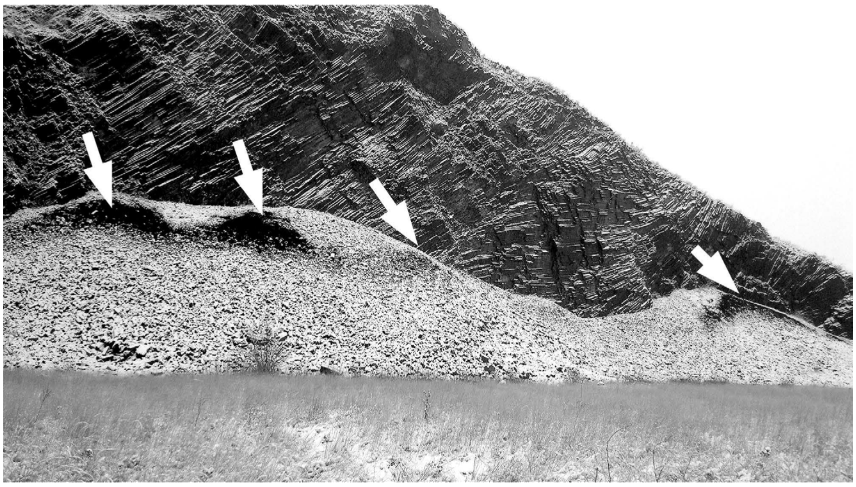
In summary, the site-specific interactions between landforms and their dynamics, on the one hand, and of microclimate, on the other, predisposes the patch-scale diversity of substrate (size and shape of rock fragments, jointing within the rockwall, and mineral content) and results in biotope diversity.

The conceptual model of these interactions is shown in Fig. 9.

The results presented confirm that landform diversity is among the key ecological factors of biotope diversity in abandoned basalt quarries because it influences the variability of other ecological factors (microclimate and substrate) and facilitates the development of plant communities that enter the site from the surrounding mosaic of biotopes (Novák and Konvička 2006). Based on these results, we suggest that reclamation strategies of abandoned quarries should be based on a combined two-step approach, including human-induced development of nature-like landforms followed by spontaneous succession. Furthermore, we assume that the original delimitation of these landforms may be distinct because the spontaneous landform dynamics may lead to diffusion of their boundaries in only a few decades.



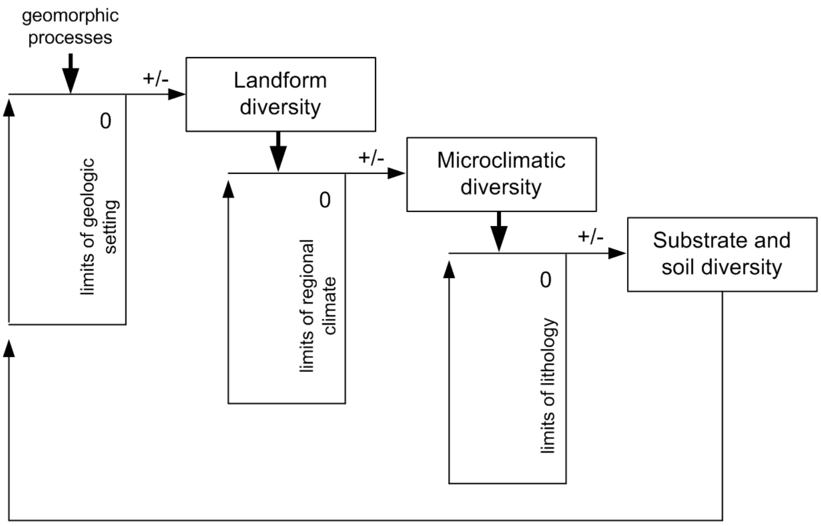
7: *Biotopes (indicated by white lines and dotted line) and main landforms (gray-hatched areas) of the studied quarry floor.*



8: *Warm air vents at the talus cones confirming the presence of air circulation patterns typical of natural scree slopes.*

IV: *Landforms, microclimate and typical biotopes at the studied quarry floor. Biotope codes according to Tab. III.*

Landform group	Subtype/location	Microclimatic specifics	Characteristic biotopes
rock cliff/ wall	W facing	high daily and moderate annual amplitudes of solar radiation and temperatures, probable water deficit (PWD) due to inclination and rock structure	B
	N-NW facing	low winter-daily and moderate summer-daily amplitudes of solar radiation, low annual incoming solar radiation, PWD	C
	S-SW facing	moderate winter-daily and low summer-daily amplitudes of solar radiation, high annual incoming solar radiation, PWD	A, B
talus cone	coarse-fine (2-5)	differential thermal regime (continuous air exchange)	E, D
	coarse (1, 7, 8)	complex air circulation (cold vents; chimney effect)	E
quarry floor	free space	lower amplitudes of temperatures due to more stable direct radiation and vegetation cover	G, H (I)
	near talus cones edge	as above, but with seasonal influence of cold air flow from the talus cone foot	F
cavity	–	low temperature amplitudes, no significant cold regime	X



9: *Conceptual model of the studied (internal) abiotic factors influencing biotope diversity.*

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Appendix I Azimuths and heights of the sun for GIS modeling of direct radiation. Explanation: A – azimuth, H – height of the sun; all values were calculated for noon on the 15th day of the month.

month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
A	176.8	175.2	176.1	178.6	180.0	177.9	175.4	176. 7	180.4	183.1	183.0	180.2
H	18.3	26.6	37.5	49.5	58.5	62.8	60.8	53.3	42.3	30.7	20.8	16.2

Appendix II List of identified species at individual biotopes of the study site. Biotopes A-I are described in detail in Fig. 7 and Tab. II.

Species	Biotope								
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
***Acer campestre* L.**						x			x
***Acer platanoides* L.**						x			
***Acinos arvensis* (Lam.) Dandy**				x					
***Agrimonia eupatoria* L.**								x	
***Achillea millefolium* L.**		x		x			x	x	
***Alyssum montanum* L.**							x		
***Anthyllis vulneraria* L.**							x		
***Apiaceae* sp.**				x					

Species	Biotope								
	A	B	C	D	E	F	G	H	I
Arrhenatherum elatius **(L.) J. Presl et C. Presl subsp.** ***elatius***		x					x	x	
Artemisia campestris **L.**	x	x	x	x	x		x		
Artemisia vulgaris **L.**		x		x				x	
Asparagus officinalis **L.**				x			x		
Asperula cynanchica **L.**		x	x	x			x		
Asplenium ruta-muraria **L.**			x						
Asplenium septentrionale **(L.) Hoffm.**		x	x		x				
Asplenium viride **Huds.**			x						
Astragalus exscapus **L.**							x		
Astragalus glycyphyllos **L.**								x	
Ballota nigra **L.**								x	
Berberis vulgaris **L.**								x	**x**
Bromus erectus **Huds.**				x			x	**x**	
Bromus sterilis **L.**									
Bryonia alba **L.**				x					
Bryum **sp.**			x						
Calamagrostis epigejos **(L.) Roth**							x	**x**	
Centaurea stoebe **L.**	x	x	x	**x**			x	**x**	
Cerastium arvense **L. subs.** ***arvense***								x	
Cerastium semidecandrum **L.**							x		
Chenopodium album **L.**				x					
Cichorium intybus **L.**								x	
Cirsium arvense **(L.) Scop.**					x			x	
Cirsium eriophorum **(L.) Scop.**								x	
Clematis vitalba **L.**						x			
Convolvulus arvensis **L.**						x			
Conyza canadensis **(L.) Cronquist**		x		x	**x**		x		
Cornus sanguinea **L.**				x		x			x
Corylus avellana **L.**						x			
Crataegus monogyna **Jacq.**				x					x
Dactylis glomerata **L.**				x			x	**x**	
Dianthus carthusianorum **L.**	x	x	x				x	x	
Dryopteris filix-mas **(L.) Schott**			x		x				
Echinops sphaerocephalus **L.**				x			x		
Echium vulgare **L.**	x	x		x			x	x	
Eryngium campestre **L.**							x	x	
Erysimum crepidifolium **Rchb.**	x	x		x	x		x		
Euonymus europaeus **L.**						x			x
Euphorbia cyparissias **L.**	x	x		x	x		x	x	
Euphrasia rostkoviana **Hayne**	x								
Falcaria vulgaris **Bernh.**							x	x	
Fallopia convolvulus **(L.) Á. Löve**				x					
Festuca pallens **Host**	x	x	x				x		
Filipendula vulgaris **Moench**							x		
Fragaria vesca **L.**								x	
Fragaria viridis **(Duchesne) Weston**							x		
Fraxinus excelsior **L.**						x			x

Species	Biotope								
	A	B	C	D	E	F	G	H	I
Galium aparine **L.**				x					
Galium verum **L.**								x	
Genista tinctoria **L.**								x	
Hieracium pilosella **L.**							x		
Hieracium sabaudum **L.**		x	x	x			x		
Hylotelephium telephium **(L.) Ohba**		x	x		x		x		
Hypericum perforatum **L.**								x	
Hypnum cupressiforme **Hedw.**			x				x		
Jovibarba globifera **(L.) J. Parnell**	x	x		x	x				
Juglans regia **L.**				x					x
Lactuca serriola **L.**		x		x					
Lactuca viminea **(L.) J. Presl et C. Presl**				x	x				
Lepidium campestre **(L.) R. Br.**		x		x			x		
Lepraria **sp.**					x				
Ligustrum vulgare **L.**				x		x			x
Linaria vulgaris **Mill.**								x	
Lithospermum arvense **L.**				x					
Lotus corniculatus **L.**							x	x	
Malus sylvestris **Mill.**									x
Medicago falcata **L.**								x	
Medicago lupulina **L.**							x		
Medicago minima **(L.) L.**								x	
Melica transsilvanica **Schur**	x	x		x					
Melilotus officinalis **(L.) Pallas**		x		x				x	
Muscari tenuiflorum **Tausch**		x		x			x		
Ononis spinosa **L.**								x	
Ornithogalum umbellatum **L.**								x	
Orobanche lutea **Baumg.**								x	
Parmelia **sp.**			x						
Phleum phleoides **(L.) Karsten**								x	
Plantago lanceolata **L.**								x	
Plantago major **L.**				x					
Plantago media **L.**								x	
Poa angustifolia **L.**			x	x	x		x		
Poa bulbosa **L.**	x	x	x	x	x		x		
Populus tremula **L.**						x			x
Potentilla anserina **L.**								x	
Potentilla arenaria **Borkh.**	x	x	x	x			x	x	
Prunus avium **(L.) L.**									x
Prunus fruticosa **Pallas**									x
Prunus spinosa **L.**				x					x
Pseudolysimachion spicatum **(L.) Opiz**							x		
Pulsatilla pratensis **(L.) Mill. subsp.** ***bohemica*** **Skalický**							x		
Pyrus pyraster **(L). Burgsdorf**									x
Quercus petraea **(Mattuschka) Liebl.**									x
Rhamnus cathartica **L.**				x		x			x
Rosa **sp.**	x	x		x					x

Species	Biotope								
	A	B	C	D	E	F	G	H	I
Rubus **sp.**						x			x
Rumex acetosa **L.**								x	
Rumex acetosella **L.**	x	x	x						
Salvia verticillata **L.**							x		
Sambucus nigra **L.**		x		x		x			x
Sanquisorba minor **Scop.**		x		x			x		
Scabiosa ochroleuca **L.**	x						x		
Securigera varia **L.**								x	
Sedum album **L.**	x	x	x	x	**x**				
Sedum sexangulare **L.**	x	x					x		
Senecio vulgaris **L.**				x	**x**				
Seseli hippomarathrum **Jacq.**			x						
Silene latifolia **Poiret subsp.** ***alba*** **(Mill.) Greuter et Burdet**								x	
Silene otites **(L.) Wib.**	x	x	x	x			x		
Silene vulgaris **(Moench) Garcke**								x	
Stachys recta **L.**		x		x			x	x	
Stipa capillata **L.**				x			x		
Symphoricarpos albus **(L.) Blake**									x
Syringa vulgaris **L.**						x			x
Taraxacum **sect.** ***ruderalia*** **Kirschner, H. Øllgaard et Štěpánek**			x	x					
Thymus pannonicus **All.**	x	x		x			x		
Tragopogon pratensis **L.**								x	
Trifolium arvense **L.**							x	x	
Trifolium repens **L.**							x	x	
Ulmus minor **Mill.**				x					x
Urtica urens **L.**				x					
Verbascum densiflorum **Bertol.**	x	x		x			x	x	
Verbascum lychnitis **L.**							x	x	
Veronica hederifolia **L.**				x					
Veronica prostrata **L.**							x	x	
Viburnum lantana **L.**						x			x
Vicia angustifolia **L.**								x	

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