New records of *Leistus montanus* STEPHENS, 1827 (Coleoptera: Carabidae) in Germany and a first insight into its habitat preference at local and landscape scale

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Abstract: *Leistus montanus* is a stenotopic ground beetle that predominantly inhabits exposed block fields in mountain ranges. Its regional distribution in Germany is still uncertain, and quantitative descriptions of its habitat are lacking. We studied block fields in two low-mountain ranges, the Black Forest and the Hunsrück, by means of hand collecting or pitfall trapping or a combination of both. A total of 145 specimens of *Leistus montanus* were found at 15 of the 23 block fields studied. *L. montanus* was recorded from three block fields in the Hunsrück mountains; this was the first record for the species in this mountain range. The species was found between 430 and 1,079 m a.s.l., with the upper limit being set by the altitude limits of the studied low-mountain ranges. *L. montanus* preferred south-orientated block fields with a relatively steep slope. Buffer measures of habitat connectivity at three radii (100 m, 500 m, 1,000 m) revealed that, at a landscape scale, more than double the amount of suitable habitat is available in the vicinity of colonized block fields than around uncolonized block fields. Populations typically required a minimum of 4,000 m² of available habitat at a 1,000 m radius. Stone density and elevation did not affect species occurrence. Females are larger than males (N = 59). General differences in body size were detected between the different study areas.

Keywords: Scree slopes, block fields, stenotopic ground beetle, habitat connectivity, habitat amount, distribution, relict species

Zusammenfassung

Leistus montanus ist ein überwiegend auf vegetationsfreien, offenen Blockhalden der Mittel- und Hochgebirge lebender Laufkäfer. Trotz der bekannten Bindung an diese Lebensräume ist dessen regionale Verbreitung innerhalb Deutschlands noch in einigen Regionen unbekannt. Vor allem fehlen bisher quantitative Beschreibungen des Lebensraums. Wir haben mittels Hand- und Fallenfang Blockhalden im Schwarzwald und im Hunsrück untersucht. Dabei wurden auf 15 von 23 Blockhalden Nachweise von *L. montanus* erbracht und insgesamt 145 Individuen nachgewiesen. Im Hunsrück konnte die Art erstmals auf drei Blockhalden nachgewiesen werden. Die Vorkommen in beiden Mittelgebirgen liegen in einer Höhe zwischen 430 und 1079 m ü. NN, wobei die Obergrenze durch die Höhe der untersuchten Mittelgebirge limitiert wird. Besiedelte Blockhalden weisen im Vergleich zu unbesiedelten Halden eine

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Süd- oder Süd-West-Orientierung und eine eher steilere Hangneigung auf. Während keine Präferenzen für Stiendichte und Höhenlage erkennbar sind, zeigt sich ein positiver Zusammenhang zwischen der Verfügbarkeit von Blockhalden auf Landschaftsebene (Radii von 100 m, 500 m, 1000 m) und der Besiedlung. Vorkommen von *L. montanus* finden sich dort, wo mindestens 4000 m² (Radius 1000 m) Blockhalden-Lebensraum zur Verfügung steht. Besiedelte Halden weisen etwa doppelt so viel geeigneten Lebensraum im Umfeld auf, wie nicht besiedelte Halden. Weibchen sind deutlich größer als die Männchen (N = 59). Unterschiede der Körpergröße zwischen den Untersuchungsgebieten lassen sich ebenfalls feststellen.

1 Introduction

Block fields (synonym for screes) represent a specific habitat in terms of physical structure and microclimatic conditions (Gude & Mäusbacher 1999). They are among the last remaining pristine habitats in Europe originating from geo-physical processes during the Pleistocene. Extreme microclimatic conditions have consequences for plants, mosses, lichens, and also for many arthropods (Lüth 1999; Molenda 1996; Möseler & Wunder 1999). Species which were probably widespread in the past have survived in block fields, e.g. beetles (Coleoptera, Carabidae: *Oreonebria* spec., *Pterostichus negligens* (Sturm, 1824), *Pterostichus panzeri* (Panzer, 1803)) and spiders (Araneae: *Acantholycosa norvegica sudetica* (L. Koch, 1875)) (Molenda 1996; Ružička & Klimeš 2005; Kastner et al. 2018). One of these relict species is *Leistus montanus* (Coleoptera: Carabidae) with highly isolated populations in the low-mountain ranges of Central Europe (Fritze & Hannig 2010; Schmidt & Trautner 2016; Trautner et al. 2014). Typical habitats of this beetle species in the UK and in alpine environments range from block fields to alpine grasslands, while in low-mountain ranges the species is predominantly found in sun-exposed block fields (Farkač & Fassati 1999; Fritze & Hannig 2010; Luff 2007). Block fields are characteristic habitats in low-mountain ranges in Central Europe and many of them are still unexplored in terms of their flora and fauna. A new record of *L. montanus* for a mountain range in Germany emerged a few years ago when by-catches of an extensive spider sampling from the Harz mountains were checked for ground beetles (Mossakowski 2017). However, little is known about the species' presence and distribution in other regions of Germany (Black Forest, Hunsrück, Odenwald, Eifel) or about its detailed habitat preferences. *L. montanus* is classified as an extremely rare species in Germany, while its global conservation status is unclear (Schmidt & Trautner 2016; Schmidt et al. 2016). As Germany probably has a national responsibility for the isolated outposts in the low-mountain ranges it is important to obtain better knowledge of these populations. Habitat requirements and data on regional distribution are useful to evaluate the conservation value of existing block fields and to develop management options when conditions are suboptimal. This paper provides new data that might contribute to a better understanding of the species' distribution and biology in Central Europe. Our specific aims were: 1) to update information on the distribution of *L. montanus* in Germany; 2) to compare conditions in block fields with and without presence of *L. montanus* in terms of slope exposition, slope angle, elevation, stone density, habitat continui-

Fig. 1: Block fields studied in the Black Forest National Park (A, Altsteigerskopf) and in the Hunsrück-Hochwald National Park (B, Vorkastell). *Leistus montanus* was found at both locations.

Tab. 1: Study sites in the Black Forest (BF) and Hunsrück (HR). The number of *L. montanus* caught using different collecting methods is also shown. * = localities within the Black Forest National Park, ± = locality within the Hunsrück-Hochwald National Park.

Region	Locality	Latitude	Longitude	Elevation	Specimens pitfall trapping (vinegar/propylenglycol)	Specimens hand collecting
BF	Nature reserve “Battert”	48.77670	8.250713	480	-	13
BF	Studentenloch*	48.637536	8.264605	920	-	0
BF	Altsteigerskopf2*	48.577588	8.218898	855	17/0	-
BF	Altsteigerskopf3*	48.574283	8.226455	951	17/0	-
BF	Altsteigerskopf4*	48.573038	8.222244	930	-/6	6
BF	Steinhalde Grimmerswald	48.599258	8.170330	660	-	9
BF	Melkereikopf2*	48.555037	8.204611	922	21/1	4
BF	Ruhesteinstrasse	48.58069	8.213920	760	-	3
BF	Seebach1	48.592465	8.177916	686	3/2	10
BF	Seebach2	48.590306	8.183472	713	0	0
BF	Seebach3	48.587354	8.182334	734	3/0	-
BF	Hornisgrinde	48.613008	8.205973	1079	0	-
BF	Karlsruher Grat	48.561101	8.189917	670	0	0
BF	Melkereikopf1*	48.556172	8.205272	960	0	0
BF	Ochsenkopf*	48.640956	8.300007	922	0	0
BF	Seibelseckle1*	48.591295	8.219724	1055	0	-
BF	Seibelseckle2*	48.590251	8.221966	1035	0	-
BF	Brandmatt	48.599492	8.169963	678	-	4
BF	Nature reserve “Scheibenfelsen”	47.917981	7.996161	720	-	8
BF	Sankt Wilhelm	47.893862	7.958722	885	-	7
HR	Vorkastell±	49.674200	7.090576	590	3	-
HR	Nature reserve “Mörschieder Burr”	49.786045	7.281968	590	4	-
HR	Nature reserve “Rosselhalde”	49.764669	7.236676	430	4	-
				Total	**81 specimens**	**64 specimens**

ty, and block field connectivity as well as habitat availability at local and landscape scale; and 3) to provide information on phenology, individual behaviour, and sexual dimorphism in body size.

2 Material and Methods

2.1 Study areas and beetle sampling

We studied seven block fields in the northern Black Forest (Black Forest National Park and adjacent areas, Table 1, Figure 1A). Five pitfall traps per site were set on 8 September and kept open until 13 October 2016 to sample ground beetles in block fields. This time period covers one of the two activity peaks per year (Fritze & Hannig 2010). Plastic cups (0.2 l) were filled with a mixture of red and white vinegar and were emptied weekly. We used no detergent because vinegar has a low surface tension compared to water. Additional hand collecting (1 h per site) was carried out at 12 block fields in September 2017 beginning at dusk. Further pitfall traps were established at 13 block fields from June to September 2017 to investigate spider assemblages (Kastner et al. 2018). We also investigated ground beetles in the by-catches. Ten pitfall traps per site were used and filled with propylenglycol. These sites comprised some which had already been sampled in 2016, but also included block fields not previously sampled. In the Hunsrück mountains

(Hunsrück-Hochwald National Park, Figure 1B) we used short-term pitfall trapping at the end of September/beginning of October to check for the presence of *Leistus montanus* in three different block fields (Table 1). Five pitfall traps (plastic cups of 0.2 l filled with a mixture of red and white vinegar) were set at each site. Altogether, we surveyed 20 block fields in the Black Forest and three block fields in the Hunsrück for presence of *L. montanus*.

2.2 Habitat conditions in block fields

In Central Europe *L. montanus* is considered to be a petrophilic (= association with stony debris) ground beetle species which inhabits block fields of different basic stone material (Fritze & Hannig 2010). Block fields are characterized by their microclimatic conditions, physical structures, and their dynamics in space and time. We defined 11 variables representing these aspects (Table 2). The parameters altitude, slope steepness, and exposition were derived from a digital terrain model interpolated from airborne laser scan data acquired in spring 2015. The return density of 25 beams/m² data allowed us to produce a highly detailed terrain model. Stone density was established through visual stereoscopic interpretation of aerial photographs acquired in spring 2015 within representative subplots of each block field (Figure 2). To account for resolution bias, individual stones

Fig. 2: Aerial photo with block field margins and subplots used for representative counts of stone density. Subplots have a 2 m radius.

were counted at a fixed scale. The ground resolution of the aerial photo enabled us to distinguish a minimum stone size of 20 cm. Mean stone density per block field was calculated for a varying number of subplots (each 2 m radius) representing, in sum, 5 % of the respective block field area. Aerial photographs from 1936, 1971-73, 1980, 1995, and 2017 were used to evaluate availability of open block field conditions over time for individual block fields. We divided sites into stable block fields, i.e. continuity of open conditions, and those that showed dynamics of forest recovery over time, thus presenting unsuitable conditions for *L. montanus* for certain time periods.

Tab. 2: Block field variables used to describe the habitat preference of *Leistus montanus*.

Variable	Description and unit	Min - Max	Mean
Slope exposition	Mean slope exposition of the block field [°]	105 – 276	197
Slope steepness	Mean slope angle of the block field [%]	13 - 43	33
Elevation	Elevation of the centre of the block field [m a.s.l.]	717 – 1079	880
Stone density	Mean stone density per block field [m²]	1.71 – 5.21	3.2
Habitat continuity	Stable or dynamic	Stable = 11 block fields; Dynamic = 4 block fields	
Area	Block field area [m²] corrected for slope angle	180 – 15,161	2,302
Horizontal distance	Shortest horizontal distance to next block field [m]	74 – 2,601	791
Slope distance	Shortest slope distance to next block field	78 – 2,668	821
Buffer-based connectivity100	Block field area at radius of 100 m from respective block field centre [m²]	135 – 13,039	2,443
Buffer-based connectivity500	Block field area at radius of 500 m from respective block field centre [m²]	135 – 14,602	4,768
Buffer-based connectivity1000	Block field area at radius of 1,000 m from respective block field centre [m²]	135 – 15,683	5,542

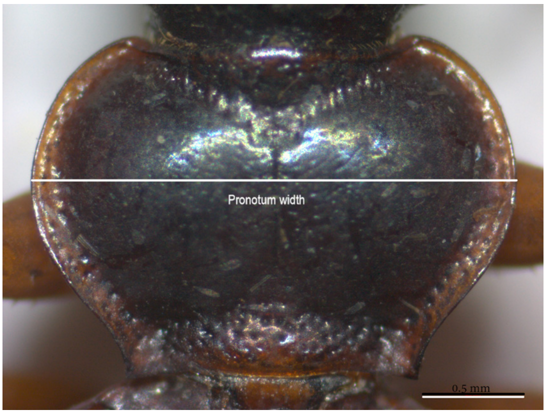

Fig. 3: Pronotum of a *Leistus montanus* female from the Black Forest. The position where maximum pronotum width was measured is shown.

Connectivity across block fields may be important for long-term survival of *L. montanus* populations. We measured the shortest horizontal distance to the next block field, and also the shortest slope distance accounting for vertical distance, i.e. using the digital terrain model for spatial correction. Habitat availability around each block field was measured within radii of 100 m, 500 m, and 1,000 m in relation to the outer margin of the block field.

2.3 Morphological measurements

We measured pronotum width of 44 females and 15 males of *L. montanus* to test for differences between sexes and for differences between the two study regions (Black Forest and Hunsrück mountains). The width of the pronotum was used as a proxy for overall body size (Fig. 3) (Knapp & Knappová 2013; Huber et al. 2010). To assess the maximum width of the pronotum, the measurement tool from tpsDig 2.31 was used for each individual. The pronotum of each individual was first photographed in a plane position using a Zeiss AxioCam Erc 5s mounted on a Zeiss Binocular. The images where then scaled using the ZEN Software by Zeiss and a scale bar was implemented for precise scaling.

2.4 Statistical analyses

Differences in habitat conditions between sites colonised and those not colonised by *L. montanus* were tested with t-tests and Wilcoxon rank-sum tests depending on the nature of the data (Crawley 2005). Linear mixed effects models (LMM) were built to analyse the linear measurements of pronotum width. We performed the analysis for sex-specific differences in pronotum width while accounting for differences between the two study areas with the lme4-Package (Bates et al. 2015) in the form of: lmer (Pronotum_width ~ Sex + (1|Origin)). Differences between the two study areas were tested with the following model: lmer (Pronotum_width ~ Origin + (1|Sex)).

3 Results

3.1 Distribution in Germany

The current centre of *Leistus montanus* distribution in Germany is in the federal state of Baden-Württemberg in the south-west of Germany. About half of the OSM (ordinance survey map 1:25,000) grid cells with *L. montanus* presence are found here (Fig. 4). Hand collecting (n = 64 specimens) and pitfall trapping (n = 81) proved the presence of *L. montanus* at 15 of the 23 block fields studied. There are new records in the northern Black Forest, where the species has only been known a few years, but where at least 10 block fields are now known to be colonised by *L. montanus*. One is located in a nature reserve (Battert) and four are located within the Black Forest National Park. One further record was made in the southern Black Forest where the species is known from different localities. We also provide the first records of *L. montanus* from three previously uninvestigated block fields in the Hunsrück mountains (Table 1).

3.2 Habitat conditions in block fields and habitat availability at landscape scale

L. montanus was not found on block fields that showed dynamics of forest recovery over time. It was recorded exclusively at block fields that were shown to provide stable habitat conditions over time. Mean exposition of slopes had no impact on colonisation (t-test, p = 0.715), but we found colonisation only on block fields orientated between 140° (south) and 276° (west). Block fields colonised by *L. montanus* had steeper slopes (mean = 36 %) than uncolonised block fields (mean = 31 %), but this was not statistically significant (t-test, p = 0.214). Mean stone density per block field ranged between 1.71 and 5.21 stones per m^2, while densities between 0.32 and 9.05 stones per m^2 were found at individual subplots within block fields. However, there was no difference in stone density between block fields colonised by *L. montanus*

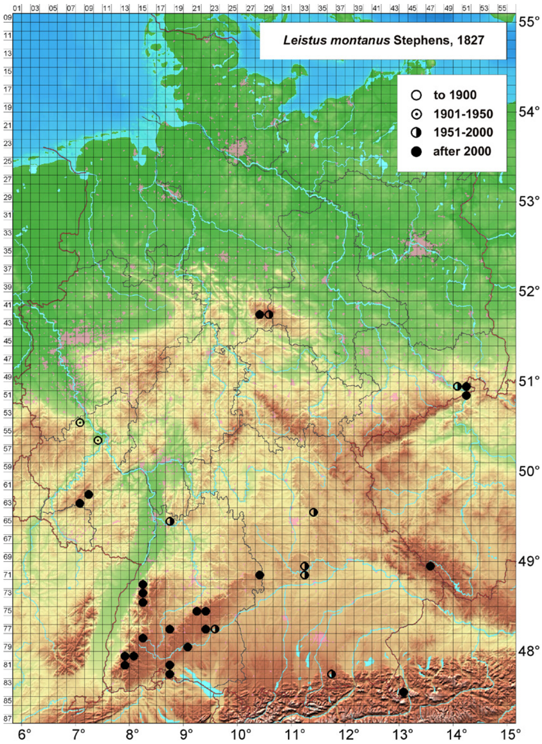

Fig. 4: Distribution of *Leistus montanus* in Germany.

(mean = 3.1) and those not colonised (mean = 3.36; t-test, p = 0.645).

Block fields in the study area showed large variation in individual size (Table 2). Block fields colonised by *L. montanus* were not larger than uncolonised fields (t-test, p = 0.25). The smallest block field inhabited by *L. montanus* was 640 m². Colonised block fields (shortest distance, mean = 303 m) tended to be better connected with other block fields

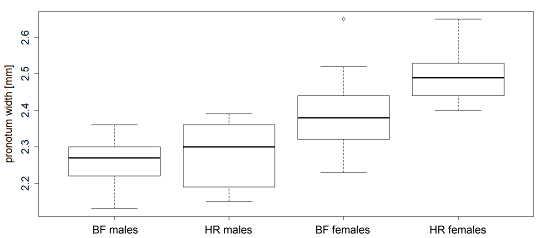

Fig. 5: Pronotum width of *Leistus montanus* females and males compared between the two study areas in the Black Forest (BF) and the Hunsrück (HR). males from BF n = 9, males from HR n = 6, females from BF n = 38, females from HR n = 6. The horizontal lines show the median, 25 % and 75 % quartiles, and the dotted lines indicate the range of the data.

than uncolonised ones (mean = 1,216 m) (t-test, p = 0.067). Furthermore, we found that habitat availability at 500 and 1,000 m buffers was different around colonised vs. uncolonised block fields. Those occupied by *L. montanus* had higher habitat availability at both spatial scales than uncolonised ones (Buffer500 p = 0.027; Buffer1000 p = 0.012). We found a minimum of 3,945 m² of available habitat at the 1,000 m buffer when the species was present.

3.3 Phenology and behaviour

From our samples we confirm that May and September are the two activity peaks in the year. We found freshly hatched specimens at the end of May. Copulation was observed in September. Autumn activity starts when rainfall has triggered collembolan activity after typical summer drought. Individual activity at the block field surface starts at dusk and continues into the night. This time-frame could thus be used for monitoring activities. Beetles sit on stones and are visible when headlights are used to search for them. After a few seconds, they try to avoid the disturbance caused by the headlights, and search for shelter. We also observed single beetles climbing trees at block field margins.

3.4 Morphological differences

Pronotum width varied between 2.23 and 2.65 mm in females (n = 44) and between 2.13 and 2.39 mm in males (n = 15). Females (mean = 2.4 mm) were in general larger than males (mean = 2.27 mm) (LMM, sex-specific fixed effect, p < 0.001, Figure 5). Specimens from the Hunsrück were larger than those from the Black Forest, when accounting for sex-specific differences (LMM, study area fixed effect, p = 0.007).

4 Discussion

Our records from previously unexplored block fields in poorly studied regions of Germany contribute to a better understanding of the distribution of *L. montanus* in Central Europe. German populations outside of the Alps are highly isolated, and assessment of the national responsibility for this species requires detailed knowledge of their distribution. *L. montanus* was not known to be present in the northern Black Forest until 2014 and we have now identified at least 10 different localities. Further records might be expected if sampling effort is increased. Other low-mountain ranges (e.g. Rhön, Thuringian Forest, Rothaar mountains, Frankian Alb) are potential areas where the species might be expected because they all have block field habitats. The new records between 430 and 1,079 m a.s.l. are in line with the known elevation range of the species (Fritze & Hannig 2010; Mossakowski 2017). The populations discovered in the Hunsrück are among the lowest sites occupied in Central Europe, although the species is generally able to colonize sites on a wide elevational range (Fritze & Hannig 2010).

A comparison of conditions between colonised and uncolonised block fields revealed that *L. montanus* has a preference for sun-exposed, steep slopes with long-lasting habitat continuity. Complex microclimatic conditions as found at one of the Frankonian populations were discussed by Harry & Trautner (2017). In the calcareous block fields of the Hersbrucker Schweiz *L. montanus* occurs together with xerothermophilic species such as *Oedipoda germanica* (Latreille, 1804) on the one hand, and together with plants of a nordic-arctic distribution and a preference for cold air such as *Saxifraga rosacea* Moench, 1794 on the other hand (Fritze & Hannig 2010).

Block fields are among the few remaining pristine habitats in Central Europe. Most of them date back to the last glaciation period when physical weathering due to frost action occurred under periglacial conditions (Gude & Mäusbacher 1999). *L. montanus* prefers these extreme conditions.

We show that habitat amount and connectivity play a crucial role for species presence. Sun-exposed steep slopes without higher vegetation represent an environment of extreme abiotic conditions. Maximum surface temperatures up to 65 °C have been recorded in block fields of the northern Black Forest (Kastner et al. 2018). Availability of prey such as spiders, machilids (Archaeognatha), and, in particular the entire group of springtails as the probable main source of prey is very limited in these habitats (Assmannn 2006; Hengeveld 1980; Loreau 1983). After a summer break in activity we observed the start of autumn activity in close association with the rise of springtail activity, especially after the first rain events at the end of August/beginning of September. By-catches from Kastner et al. (2018) and catches from pitfall trapping in 2016 revealed that *L. montanus* is the most frequent and thus the characteristic ground beetle in block fields of the northern Black Forest. No other ground beetle is found at high densities under these extreme conditions. *Oreonebria boschi* Winkler in Horion 1949, another ground beetle, was sometimes found at the same sites in the northern Black Forest but is restricted to sites with an air-conditioning effect, and is not dependent on open, sun-exposed block fields. The spiny scree wolf spider *Acantholycosa norvegica sudetica* is among the few stenotopic invertebrates which inhabits block fields, but it is able to colonize a wider spectrum of block fields than *L. montanus* (Kastner et al. 2018).

An interesting finding was that habitat availability at local and landscape scale influenced occupancy of this stenotopic ground beetle species. Habitat availability, here block field area, around individual study plots is probably a critical feature that determines occupancy patterns of individual species as it is generally one of the main predictors of species density (Fahrig 2013; Watling et al. 2020). We found stronger evidence for effects of habitat availability than for isolation or patch size. The habitat preference of the stenotopic ground beetle *L. montanus* is quite clear and we also have a good understanding of the matrix for unsuitable habitat. Habitat availability may play a role for the long-term survival of this ground beetle if there is strong variation in population size at individual block fields or if single populations go extinct. Although it is macropterous, this beetle is likely not able to fly because of its relatively short hindwings (Assmann 2006; Paill 2012). Nowadays, it is difficult for this species to colonise isolated block fields because of its strong habitat preference. It is important to protect habitat complexes and particularly large block fields. Therefore, for all sites with species presence it is recommended that protection and habitat management measures are reviewed to ensure preservation of populations (Harry & Trautner 2017). Block fields are directly influenced by human activities such as construction of new roads and hiking trails, removal of stones, litter disposal, and climbing activities. Shrub encroachment and subsequent forest succession at block field margins triggered by increasing airborne nitrogen deposition might decrease available habitat for *L. montanus* (Harry & Trautner 2017). This is already a problem for populations of *Leistus piceus* in some parts of the Fichtelgebirge, where building activities and forest succession have considerably reduced the block field area (Fritze & Blick 2010). Habitat loss will have negative consequences for the long-term survival of any stenotopic ground beetle inhabiting block fields. Morphological differentiation of *L. montanus* specimens between the study regions probably indicates isolated populations with local adaptations. We believe that protection of all block field habitats is necessary to retain such adaptations and to maintain a high level of available habitat for this species of national responsibility.

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