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Not too much vertical space left: the maximum recorded elevation for *Lacerta agilis* Linnaeus, 1758 in Central Europe

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The Sand Lizard (*Lacerta agilis* Linnaeus, 1758) is considered one of the most common and widely distributed lizards in the western Palearctic (Bischoff, 1988; Sindaco and Jeremčenko, 2008). The species ranges from Great Britain and the Iberian Peninsula to Lake Baikal, Mongolia, and northwestern China. Its northern distribution extends across France, Belgium, the Netherlands, Denmark, Sweden, and northern Estonia, reaching as far as northern Russia along similar latitudinal lines. In the south, the species is found in the Balkans, with its southernmost limits in northern Greece, northern Türkiye, Armenia, Azerbaijan, the western and northern Caspian Sea, Kazakhstan, and extending to China (Rehák, 1992; Sindaco and Jeremčenko, 2008; Moravec, 2015). It inhabits a variety of habitats from sea level to high mountains. Throughout its range, the species exhibits a complex taxonomy with 12 existing subspecies, including some evolutionarily divergent lineages for which possible elevation at the species level has been suggested (Kalyabina-Hauf et al., 2001). Significant morphological variation among populations, and further genetic analyses suggest that taxonomic revisions may be necessary (Andres et al., 2014).

Traditionally, the subspecies *L. a. agilis* and *L. a. argus* (Laurenti, 1768) have been associated with Central Europe (e.g., Blanke and Fearnley, 2015). However, due to the unresolved status of these subspecies (stemming from a combination of molecular data, morphology, and distribution patterns), defining their current range is challenging. Phylogeographic studies by Kalyabina-Hauf et al. (2001) and Andres et al. (2014) suggested that both subspecies may occur in this region. However, a comprehensive phylogeographic analysis and taxonomic evaluation beyond the aforementioned studies is lacking. The presence of several distinct evolutionary lineages in the broader Central European area further complicates the subspecific taxonomic status and geographic distribution of these subspecies.

In Central Europe, *L. agilis* has been recorded at elevations up to 1700 m, particularly in Austria (Cabela et al., 2001) and Germany (Blanke, 2010). In Poland, it is found at elevations up to 1500 m (Głowaciński and Rafinski, 2003), while in the Czech Republic and Hungary, it has been recorded at elevations up to 900 m (Méhely, 1918; Moravec, 2015). In Slovakia, the species has been recorded at elevations up to 1500 m in the High Tatra Mountains (Kautman and Smolinský, 2010), the Low Tatra Mountains (Ferianc, 1946; Ohniště Massif at 1440 m: Ján Kautman, unpubl. data), and the Great Fatra Mountains (Radúch and Kadlečík, 1989), common at elevations of 400–500 m (Daniel Jablonski, unpubl. data). The species has also been recorded at an elevation of 2500 m in the Romanian Carpathians (Fuhn and Vancea, 1961) and up to 2800 m in the Pirin Mountains of Bulgaria (Tzankov, 2007; Petrov, 2007). However, due to the presence of distinct evolutionary lineages exhibiting deeper divergences (and possibly reflecting different ecological traits or adaptations), these Balkan populations may not be directly comparable with those from Central Europe. The highest global elevation for the species has been recorded in Kyrgyzstan at Kurmenty Pass, at 3312 m (Yakovleva, 1964).

In this study, we report an exceptional observation of *L. agilis* at Slavkovský štít in the High Tatras (Carpathian Mountains), Slovakia. On 27 August 2024 at approximately 10:30 h, an adult male was observed and photographed by a local tourist near the mountain peak at an elevation of 2452 m (49.1661°N, 20.1847°E; Fig. 1A). The weather was sunny, with a temperature of about 27°C. This surprising observation represents the highest recorded elevation for the species in Slovakia (Fig. 1B) and for Central Europe and is one of the highest in its entire range.

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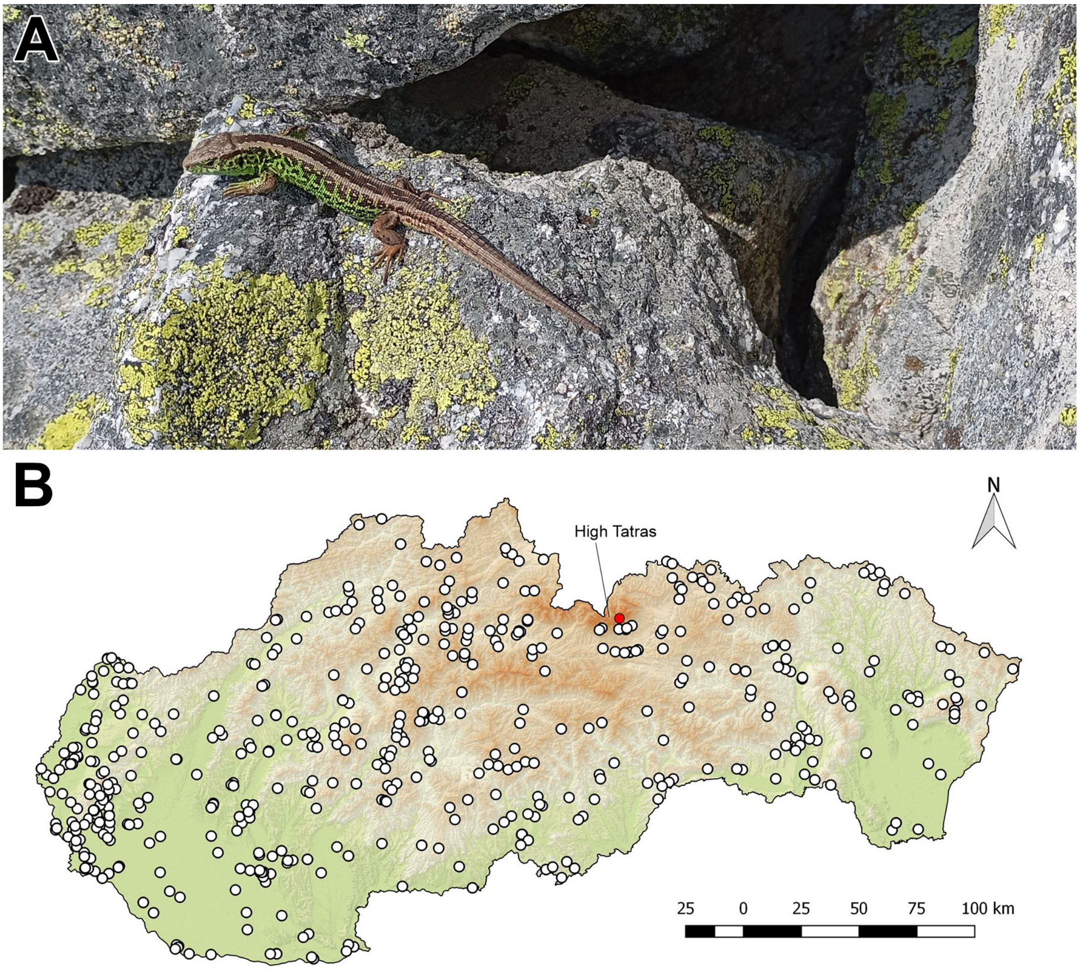

Figure 1. (A) Adult male *Lacerta agilis* from Slavkovský štít in the High Tatras, Slovakia, photographed at an elevation of 2452 m. (B) The distribution of *L. agilis* in Slovakia based on the literature and citizen science data (white dots; unpublished database) with the red circle marking the record from the High Tatras.

This exceptional single elevational record (the highest point in Slovakia is Gerlach Peak at 2655 m) represents a vertical range extension for the species of approximately 1000 m compared to previous records from the High Tatras. Kautman and Smolinský (2010) reported the species from Mengusovská dolina and Štrbské pleso at 1500 and 1355 m, respectively. The observed elevation is also atypical for *L. agilis* in a Central European context due to the mountain microclimate and the habitat characteristics shaped by contrasting temperature variations between day and night and the alpine, rocky environments above the tree line (Fig. 1B). High mountain elevations in Slovakia are predominantly inhabited by two reptile species, *Zootoca vivipara* (Jacquin, 1787) and *Vipera berus* (Linnaeus, 1758). Generally, sightings of *L. agilis* in Slovakia above 1500 m are very rare, as also noted by Lác et al. (2017).

Lacerta agilis in Central Europe prefers areas with warm and dry conditions, low to moderate rainfall, high solar radiation, and humidity levels that do not hinder thermoregulation. Interestingly, as suggested by Májsky (2021), *L. agilis* has become less common at lower elevations in the country. According to Májsky (2021) and supported by historical data of other authors (see Lác et al., 2017), *L. agilis* was a common species across Slovakia from the lowlands to hilly areas during the second half of the 20th Century. Although extensive, long-term, fieldwork-based studies that could directly confirm this for Central Europe are lacking, population densities of *L. agilis* may decline at lower elevations and the range may shrink in the future due to the loss of suitable habitats, as suggested by recent simulations from Western Europe (Boyer et al., 2023).

Thus, we utilized database of distribution and elevational records for *L. agilis* in Slovakia, which includes data from the published literature and citizen science platforms (iNaturalist.org, nahuby.sk) spanning 1956–2024 (Fig. 1B). To investigate whether there was an elevational shift between two defined periods (1956–1990 and 1991–2024), we analysed a total of 1401 elevation records from the complete (unbalanced) dataset using the statistical software R v4.3.3 (R Core Team, 2024). To visualize elevational distributions, violin and boxplots were generated using the *ggplot2* package in R (Wickham, 2016), displaying median elevations for each dataset and period, with overlaid data points to show the spread of values. Statistical tests on the unbalanced dataset indicated a statistically significant result in the opposite direction to what was expected (from Mdn = 464 m in 1956–1990 to Mdn = 339 m in 1991–2024; Fig. 2A). The Kruskal-Wallis's rank sum test yielded a Chi-squared value of 15.286 ($df = 2$, $p < 0.001$), and the Wilcoxon rank sum test produced $W = 64465$ and $p < 0.001$. This discrepancy may be attributed to the unequal distribution of data (historical vs. recent) across the two time periods.

To address this limitation, we prepared a balanced dataset comprising 703 records, equally distributed between the two investigated periods. For balanced comparisons, data were divided into 500-m elevation bins, with a maximum of 50 data points per bin per period. When fewer records were available within a bin, all records were included. The sampling process was carried out using the *dplyr* package in R (Wickham et al., 2023) and the resulting balanced datasets were saved for further analysis. Analysis of the balanced dataset indicated an increase in the median elevation for *Lacerta agilis* distribution between the two periods, from Mdn = 436 m (1956–1990) to Mdn = 562 m (1991–2024) (Fig. 2B). However, statistical tests provided no significant evidence to support this observed shift: the Kruskal-Wallis's rank sum test produced a Chi-squared value of 3.5255 ($df = 2$, $p = 0.1716$), and the Wilcoxon rank sum test with continuity correction yielded $W = 4062$ and $p = 0.1294$. These discrepancies may be explained by the combined sampling approach and the lack of systematic data collection in the past. For example, it is well known that, historically, data on common species, such as *L. agilis*, were often not collected in detail (Lác and Lechovič, 1964), as these species were considered widespread in lowlands (Lác et al., 2017 mentioning the presence of *L. agilis* above 700 m as very rare). When data were collected, they often originated from locations where the species were perceived as rare or uncommon. Additionally, the quality and precision of historical data likely contributed to these inconsistencies. Thus, further systematic data collection or other statistical approaches will be necessary to draw more robust conclusions regarding potential altitudinal shifts in *L. agilis* distributions over time.

On the other hand, our results may suggest a trend of upward extension in the species' elevation range, as prevalent for other species that were more common in lowlands in the past but are now found at higher elevations, including amphibians (Tiberti et al., 2021) or even the tick *Ixodes ricinus* (Lukan et al., 2010). Factors contributing to the possible species decline at lower elevations may, however, include not only rising average temperatures but also habitat fragmentation, agricultural activities, an increasing number of domestic cats, and climate change-driven heightened competition with *L. viridis* (Laurenti, 1768), which exerts both competitive and predation pressures on *L. agilis* (Májsky, 2021).

We can thus hypothesise that climate warming may make high-elevation habitats more suitable in the future for certain species that are more influenced by temperature and humidity compared to others (Sillero, 2021). Therefore, it is essential to monitor this potential trend through direct field observations and compare it later with historical data. Such occurrences may become more common if the factors mentioned, particularly rising temperatures, continue to increase in prevalence.

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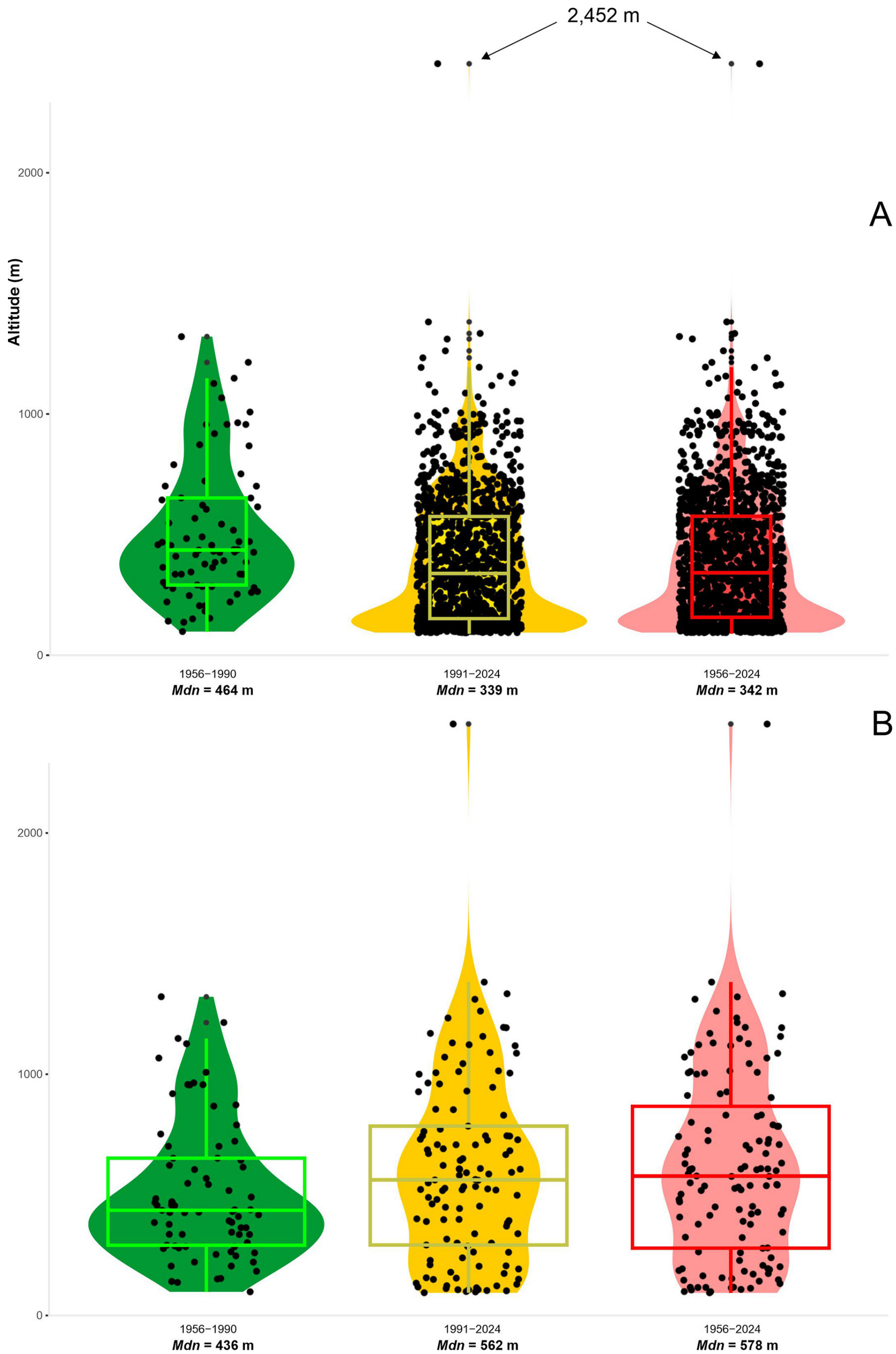

Figure 2. Combined violin and box plots illustrating altitude distributions of *Lacerta agilis* from Slovakia for three time periods: 1956–1990 (green), 1991–2024 (yellow), and 1956–2024 (red). The plots are based on (A) unbalanced and (B) balanced datasets. Black dots represent individual data points, with an outlier recorded at 2,452 m (reported in this study). Embedded box plots within the violin plots display the median (*Mdn*) and interquartile range (IQR), with whiskers extending to 1.5 times the IQR.

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