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Original research article

Estimating population abundance and monitoring population trends of endangered, elusive subterranean mammals (Rodentia: Spalacinae: *Nannospalax*) using HRAMN methodology

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A R T I C L E I N F O

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A B S T R A C T

Monitoring rare or endangered species is vital for biodiversity conservation, but it is particularly challenging for hidden or elusive species. The subterranean Eurasian blind mole rats are such species. The newly identified endemic species of this group found in the Pannonian Basin (Central Europe) are highly threatened by extinction. Their concealed lifestyle complicates population monitoring, yet such data are crucial for their conservation. To address this problem, a new methodology called HRAMN was introduced, utilizing complex aerial cartographic surveys. The method was tested in two protected areas in Eastern Hungary, home of the endangered Hungarian blind mole rat (*Nannospalax hungaricus hungaricus*). HRAMN involves collecting data through aerial surveys and producing high-resolution orthophoto mosaics and digital surface models. These data allowed the identification of blind mole rat mounds and the monitoring of population trends. The HRAMN methodology proved to be a highly effective replacement for traditional full-field surveys of blind mole rat habitats. It is particularly useful for monitoring large areas, which had been previously unfeasible. However, certain limiting factors occurred in blind mole rat habitats that require field presence and control, even with the aerial imagery-based HRAMN method. Recommendations have been made to address those limiting factors that have been identified. HRAMN methodology not only enhances survey accuracy but also allows for frequent monitoring, providing unprecedented detail on the population dynamics of these rodents. Additionally, the study explored the relationship between the spatial patterns of the blind mole rat mounds and their habitats, offering deeper insights into their ecology and potentially aiding in the development of more effective conservation strategies.

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1. Introduction

The monitoring of the status of natural values, or changes in their status, is a key task of nature conservation (Yoccoz et al., 2001), and is of particular importance for rare or endangered species (Schemske et al., 1994). Knowledge of changes and fluctuations in abundance and distribution over time for species of conservation importance is essential for the accurate and exact definition of practical conservation tasks and priorities (Yoccoz et al., 2001). In the case of certain organisms, because of their cryptic behaviour, monitoring can be especially challenging (Mills et al., 2000).

Eurasian blind mole rats (Rodentia: Spalacinae) are animals with exactly such a hidden lifestyle (Fig. 1.A). For a long time, European representatives of the genus *Nannospalax* have suffered from a severe data deficiency from the conservation point of view (Kryštufek and Amori, 2017). For example, their taxonomy was unclear until lately, which, in turn, threatened that overlooked species with a small distribution in the group would drift into a critical situation or may even become extinct in the absence of effective measures. Based on a distribution-wide representative sampling, multilocus phylogenetics and statistical species delineation, the European members of the genus *Nannospalax* were classified into three distinct superspecies, with separate phylogenetic lineages representing a complex of true biological species, and 11 well-separated distinct species, all are endemic to Europe (Németh et al., 2024). Many of the newly recognized taxa are characterised by very restricted distribution and declining populations (Csorba et al., 2023), which poses a significant new challenge for the conservation of Europe's biodiversity.

Eurasian blind mole rats have cylindrically shaped bodies with no external ears, a vestigial tail, and very short legs. They have large, chisel-shaped incisors, which they use to dig their tunnels (Fig. 1.A). Blind mole rats are completely blind and spend their entire life in their complex and extensive tunnel system built underground. They push the loose soil they excavate to the surface to get rid of it, creating the mounds that, are remarkable features of the tunnel systems (Topachevskii, 1969). Strictly solitary, territorial animals,

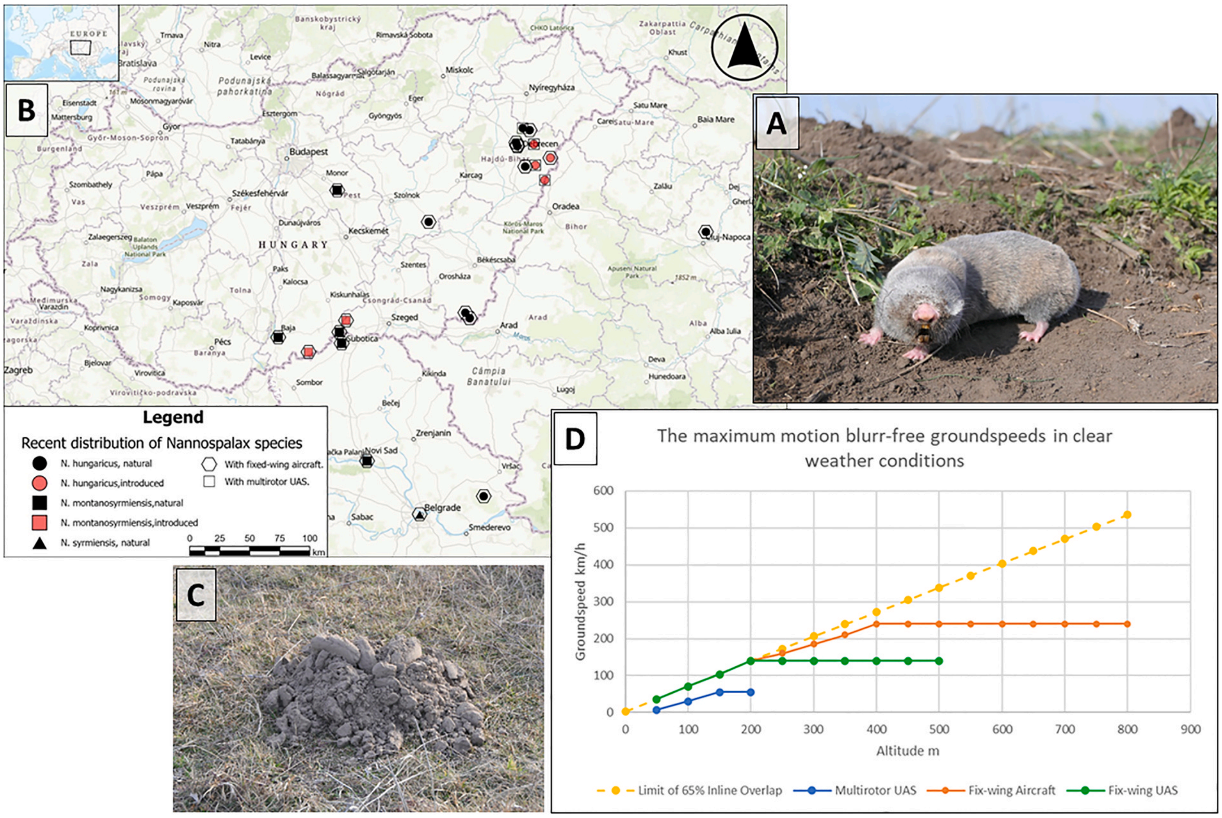

Fig. 1. The recent distribution of endemic blind mole rat species of the Pannonian Basin and the perspectives for monitoring their populations. **A:** Current distribution of the Pannonian basin endemic Hungarian- (*N. hungaricus hungaricus*) marked with dots, the Vojvodina- (*N. montanosyrmiensis*) marked with square and Srem blind mole rat (*N. syrmiensis*) marked with triangle (based on Csorba et al., 2023.). Black-coloured symbols show the natural populations, while red-coloured symbols show the reintroduced populations. The hexagons or squares drawn around the symbols indicate the type of platforms that are recommended to use during aerial surveys for regular monitoring of the given population. **B:** General appearance of an individual of the highly specialised strictly subterranean Hungarian blind mole rat (*N. hungaricus hungaricus*). **C:** Typical blind mole rat mound from one of the study sites (Blind mole rat Reserve of Hajdúbagos). **D:** The applied flight altitudes and speed limits for various platforms under clear weather conditions. The table includes the speed limit beyond which we cannot guarantee at least 65 % overlap within the flight lines (after Bakó et al. 2021). (Our present surveys are typically conducted with at least 90 % overlap within the flight lines but 65 % overlap is indeed a safety limit in terms of photogrammetric image processing.).

each individual has its own tunnel system, which is protected from its conspecifics (Nevo et al., 1975, 1986, Topachevskii, 1969). Blind mole rats live exclusively on a plant diet, eating underground parts of plants, roots modified for storage, tubers, bulbs, and rhizomes. They survive the unfavourable periods of the year by living on plant parts stored in special chambers (Horváth et al., 2007, Németh et al., 2013, Topachevskii, 1969). These food stores are collected during the more favourable periods of the year, typically with precipitation and suitable temperatures (neither too cold nor too hot). This is the period when their burrowing activity is higher, as indicated by the appearance of more mounds on the surface (Heth, 1989, Nevo, 1991, Šklíba et al., 2016, Zuri, 1993, Zuri and Terkel, 1997). Tunnelling activity also increases during the breeding season, resulting in an increased amount of mounds observed on the surface. In the Near East it begins after the first winter rains (Nevo, 1961), in Central and Eastern Europe it is observed to occur from January till early March (Moldován, 2014, Topachevskii, 1969).

The exclusively subterranean lifestyle of Eurasian blind mole rats (Topachevskii, 1969) makes it very difficult to estimate the number of individuals within a given population, as well as to monitor the changes in population numbers. However, some of the recently identified species, especially in the northern part of the European distribution area already have critical conservation status (Csorba et al., 2023), which makes reliable population data very necessary. The endemic blind mole rat taxa of the Pannonian or Carpathian Basin (a topographically well-defined, predominantly lowland geographic unit in Central Europe) the Hungarian blind mole rat (*Nannospalax hungaricus hungaricus* Nehring, 1898), the Vojvodina blind mole rat (*N. montanosyrmiensis* Savić and Soldatović 1974) and the Srem blind mole rat (*N. syrmiensis* Méhely, 1909), are all seriously threatened according to a recent study (Csorba et al., 2023). Although these subterranean rodents were once widespread in the Pannonian Basin, their conservation status deteriorated considerably into a serious situation because of the transformation and disappearance of their dry grassland habitats (Csorba et al., 2015, Németh et al., 2013). By now, these endemic taxa of blind mole rats are among the rarest and most threatened animals in the region (Fig. 1.B).

The considerable need for population data is well illustrated by the fact that the first attempts to monitor blind mole rat populations in Hungary (Palotás, 1982, 1987, Végh, 1986) and in Serbia (Mikes et al., 1982) started already in the early 1980s. Efforts to monitor according to a uniform methodology gained new momentum around the turn of the millennium in both countries (Bihari et al., 2009, Delić, 2007, Horváth, 1999, Horváth and Vadnay, 2001). These methods focused on the mounds of the blind mole rats, which are the only signs of the animals' presence that could be seen even from the surface (Fig. 1.C). During the field surveys the number and position of the mounds were tracked (see the detailed summary of the monitoring methodologies in Moldován et al., 2021). All of this was in line with the methods used in other regions of the blind mole rats distribution to estimate or monitor the number of individuals within a population (Zuri and Terkel, 1996, 1997). However, an Israeli study, where the activities of blind mole rats were monitored by radio-telemetry transmitters, pointed out that it could be problematic to accurately map the territory of the animals and to separate the different individuals from each other based on solely the registration of the mounds (Zuri and Terkel, 1996). Due to these methodological difficulties and other uncertainties arising during the field surveys, several attempts have been made in Hungary during the last decade to develop alternative methods that can be used to monitor blind mole rat populations more objectively (Moldován et al., 2021). These ranged from the estimation of the number of individuals using aerial photographs to the use of ground-penetrating radar (Boldog, 2011, Páll and Sipos, 2017). However, so far none of the new approaches has been widely adopted (Moldován et al., 2021). In addition, the still widely used methods based on recording the position of the mounds with a manual navigation device have such difficulties and methodological limitations that make sufficiently frequent regular monitoring of these threatened rodents quite difficult (Moldován et al., 2021). For example, populations located in larger habitats are crucial for the preservation of these endangered animals, however, with the currently used monitoring methods, it is almost impossible to assess them often enough (e.g. multiple times within a year).

To manage these issues, we propose a new methodology, which might address these problems. A specific technique called HRAMN, developed in the Central European region since 2008, based on complex aerial cartographic, geodetic, and field methods, could provide a solution (Bakó et al., 2021). (The methods detailed description will be found in the Methods.) We assumed that this method would not only make the surveys more accurate but also that they could be carried out with sufficient frequency so that we could look into the population dynamics of these endangered rodents with unprecedented detail.

2. Material and methods

2.1. Study sites

The study sites where the bind mole rat monitoring methodology was tested were located in a protected area near the settlement of Hajdúbagos and another one in the vicinity of Debrecen, close to the neighbourhood of Józsa (both are in Hajdú-Bihar county, NE Hungary). Both sites are located within the Pannonian Biogeographic Region (European Environment Agency, 2002).

The Blind mole rat Reserve of Hajdúbagos is found north of the settlement of Hajdúbagos (E Hungary) and is the oldest protected area in Hungary established directly for the conservation of these threatened rodents. The protected area was established in 1976 and consists of 265.4 ha of sand dune pasture with Pannonic sand steppe vegetation. Vegetation of the study sites is defined according to Annex I of the European Union's Habitats Directive (Commission of the European Communities, 2003). The site is also part of the European Union Natura 2000 protected area network under the ID. number HUHN20017. The site is grazed by cattle and sheep.

The valuable grassland near Debrecen-Józsa has been protected locally since 1992. The site is also part of the pan-European Natura 2000 protected area network under the ID. number HUHN20122. The area of nearly 373 ha is covered by diverse vegetation, but the higher parts of the area are covered by Pannonic loess steppe vegetation, which is the home of special, now rare steppe animals. The area is mowed and partially grazed by cattle.

In both sites, the *Nannospalax hungaricus hungaricus*, the Pannonian basin endemic subspecies of the Hungarian blind mole rat (*N. hungaricus*) occurs (Fig. 1.B). This species and subspecies have only recently been identified and separated (Németh et al., 2024). However, due to the rapid loss of its habitat over the last 150 years, it is a seriously threatened animal (Németh et al., 2013, Csorba et al., 2023). Based on the most recent information and following the categories and criteria of the IUCN Red List of Threatened Species the proposed global-scale conservation status of the subspecies is Endangered (EN) (Csorba et al., 2023).

2.2. Data collection with HRAMN methodology

The HRAMN (High-Resolution Aerial Monitoring Network) methodology has been developed and is applied in three EU member states (Austria, Hungary, and Romania) to document the sample sites through high-resolution aerial mapping of landscape details with on-site validation to monitor natural and landscape values, as well as the ecosystem services of near-natural and anthropogenic areas. The network classifies the sample areas as natural values into five categories: (1) degraded areas, (2) areas affected by environmental reconstruction, (3) sample areas for landscape and (4) cultural heritage protection, and (5) sample areas for agriculture, forest management and water management sustainability studies. However, such indicators are selected that can be used as arguments in spatial planning and municipal regulation, and in models that are valuable for future research. During the habitat surveys of the Hungarian blind mole rats, we create the HRAMN's classic geo-informatics files, i.e., we do not differ in methodology from remote sensing products prepared in other types of sample areas.

We surveyed the selected Hungarian blind mole rat habitats during the spring of 2023 using aerial photographs processed through photogrammetric methods to validate a procedure for future application to all habitats across Hungary. The surveys were carried out during the spring period when the populations of blind mole rats are traditionally monitored in Hungary to allow comparison of results. The survey utilized the procedures of HRAMN, which involved expanding the digital archive of the relevant national park directorate alongside the HRAMN database. This expansion included the addition of map layers for (1) orthophoto mosaics, (2) Digital Terrain Models (DTMs), (3) Digital Surface Models (DSMs), (4) point map layers indicating the locations of blind mole rat mounds, and (5) spot maps identifying specific areas impacted by dense vegetation or mounds created by accompanying subterranean mammal species for each designated flight date.

When mapping of more than four study sites was planned for a given single day (e.g. because it was also necessary to assess study sites for research involving other threatened species), the aerial surveys were conducted using fixed-wing aircraft such as Cessna 182, Cessna 210, Piper PA-32, and Piper PA-34. In such cases, where it was legally permissible, large-scale Interspect fixed-wing UAS (Unmanned Aircraft System) was also applied. For the survey of only one to four areas in a day, we utilise DJI Mavic 3E RTK and Autel EVO II Pro Rugged Bundle RTK V3 multirotor UAS. Despite requiring significantly longer flight times and about fourteen times more images due to their lower image resolution and dynamic range, multirotor UAS provide consistent spatial resolution in RGB (red, green, and blue bands of true colour) orthophoto mosaics across all aerial platforms. Specifically, this spatial resolution ranges from 0.5 to 1 cm. This precision was necessary because studies conducted on other species using the same methodology showed that lower spatial resolution greatly distorted the results (Bakó et al., 2014, 2020). In contrast, fixed-wing aircraft can carry heavier, higher-quality cameras. The choice of platform is justified by the requirements for cost-effectiveness and survey speed. When surveying large areas or numerous small areas within a short period, fixed-wing platforms are clearly more cost-effective, and the quality of the images better supports evaluation. If the survey timeframe is extensive or there are not many large areas to cover, then the use of UAS is more economical. We used pre-calibrated high-speed readout 100 MP CMOS cameras for the survey with a 30–250 mm focal length lens (depending on the flight altitude) 320 ISO speed; automated exposure time in the 1/1200–1/8000 interval based on the ground speed, and fixed aperture size. The aerial survey altitude ranges from 60 to 800 m above ground level, depending on the presence of any sensitive animal species at the site and the type of platform being used. In the case of fixed-wing aircraft, the ground speed ranges from 120 to 240 km/h, where the upper limit is determined by the aircraft's capabilities. For fixed-wing UAS, the speed ranges from 40 to 140 km/h, where the upper limit is determined by factors such as achievable motion blur-free photography at the given altitude and lighting conditions, as well as the realization of overlap, influenced by the camera's readout speed (Fig. 1.D). For multirotor UAS, the speed ranges from 7 to 55 km/h, depending on lighting conditions. The aerial surveys using UAS were applied in a fully automatic flight with image overlap of 90 % and sidelap of 75 % to ensure photogrammetric processing later. Image capture is always conducted with direct georeferencing, meaning that in addition to the camera's internal parameters, inclinations at the time of exposure, and the coordinates and altitude above sea level of the image acquisition location are also recorded. This is done to facilitate faster and geometrically more accurate photogrammetric processing. The photogrammetric procedure for each study site is carried out using the bundle block adjustment method, and field geodetic quality control confirms that an RMSE (Root Mean Squared Error, accuracy) of 20 cm can be maintained for geometric reliability in orthophoto mosaics. In this process, which is a statistical measure of the accuracy of the prediction, we use the square root of the mean squared prediction errors, which should be as small as possible. So close that it approximates the average deviation of the predicted values from the measured values. After the interpolation model has been estimated from all the points, the value of the predicted point is hidden, and the remaining points are used to predict the value of the hidden point. The prediction is then compared to the measured value. This process is repeated for all orthophoto mosaics.

2.3. Data processing and statistical analysis

The aim of the data collection during the aerial survey was to create an orthophoto mosaic of the study areas with a spatial resolution of 0.5–1 cm, a geometric reliability of RMSE 20 cm, and a surface model with a spatial resolution of at least 20–35 cm. The reason why RMSE is higher than spatial resolution is that landmarks can only be identified in images described by multiple pixels.

Thus, photogrammetry software cannot reconstruct geometry more accurately than a pixel. In addition, the resolution of the field models will always be lower than that of the orthophoto. To generate the orthophoto, we used high-density 12–100 MP aerial photographs. In order to produce the digital terrain model (DTM), we used the improved version of the surface model from the photogrammetric process with field qualification, and the filtered product of the point cloud, or, in some cases, the point cloud produced with a static field laser scanner, transformed into a classified digital terrain model. However, the finished DTM needs to be further refined. Due to the resolution, as well as the trees, groups of bushes, and other anthropogenic elements in the area (e.g. well, corral, electric pole), the 3D model was distorted in several places. To eliminate these, we created a contour map from the DTM using geospatial information procedures. The polylines with different values were set to a production size of 1 cm, from which the outstanding values of the surface model were selected. After the selection, we regenerated our first DTM model for the cleared and stripped surface from the left contours with the help of the Quantum GIS software (QGIS Development Team 2013). Thus, with the help of this data, we were able to create the file of the exposure of the area, as well as the file of slope percentage and angle of slope. The totality of these data formed the basis of the micro and macro water flow mapping of the area. With the help of the cleared files, the GIS software mapped micro watercourses until a precision of 0.5 cm, which represents the lower physical boundary of the geoprocess. However, these lowest values were filtered out for better handling; therefore, the drainage model only represents the higher watercourses of the mapping order.

2.4. Remote detection of blind mole rat mounds

Using digital orthophoto-mosaics, we focused on the detection of signs of the presence of blind mole rats, specifically on the detection of blind mole rat mounds, which are about 15–50 cm in diameter. We created a vector graphic target map with visual interpretation, which serves as a learning database for the future development of an evaluation software using artificial intelligence. For the analyses presented in the current manuscript, the positions of blind mole rat mounds were collected using a manual method. In the aerial images of our study sites, mounds are visible in two ways. In the sandy habitats near Hajdúbagos mounds are light spots of sandy soil on a darker matrix of the vegetation, while on the images of the heavy, loess-based chernozem soil habitat near Debrecen-Józsa mounds are dark spots on a lighter matrix of the vegetation. The mounds recorded by the aerial survey were verified in the field within a week.

2.5. Hot spot analysis

To better understand the relationship between the spatial pattern of the blind mole rat mounds and habitat topography (e.g. slope steepness), a Hot Spot Analysis was conducted.

For the Hot Spot Analysis, we are using the ArcGIS tool sets (ArcGIS Pro 3.03.). Firstly, we collocated the sample points in the area with the Integrate tool. After that, we created a collection shape with the Collect event tool, and we got the base shapes for the Hot Spot Analysis. Before we ran the analysis, our process was tested with an Incremental Spatial Autocorrelation proceeding tool. In that density tool, we provide the radius value in the Hajdúbagos sample site 20 m, and in the Debrecen-Józsa site 25 m. All distance measurements are based on feature centroids and the default Beginning Distance parameter value is the smallest distance that will ensure every feature has at least one neighbouring feature. This is generally a good choice because we have sample area polygons to determine these locations.

For the Hot Spot Analysis, we use the collection shapes. The Optimised Hot Spot Analysis examines the spatial distribution of the features and computes the average distance that would yield K neighbours for each feature. With the help of that tool, we created the Hot and Cold Spot Analysis for the sample sites.

3. Results

3.1. Registration of blind mole rat mounds

During the surveys, 20 mega-pixel (MP) images were taken for multicopters UAS, while 60 MP images for fixed-wing UAS on the first flight, and 100 MP images later during all the other flights. Thus, in the case of the multicopter UAS survey of the Blind mole rat Reserve of Hajdúbagos on 27.04.2023, 5696 pieces and 70.1 gigabytes (GB) size of each vertical camera axis images were collected. The evaluation of that amount of data took 29 hours to process. In comparison, the 3012 pieces of images, all have 63.7 GB size of the fixed-wing UAS of the same study site at the same period can be processed in 4 hours with the same workstation. The average multicopter flight of the study site near Hajdúbagos lasted a little over 4 hours (180 minutes of active photography, 45 minutes of take-off, landing, and 15 minutes of preparation) and was accomplished with 9 take-offs. The fixed-wing UAS flight took on average 41 minutes in the same area and was accomplished with two take-offs.

For the habitat of Debrecen-Józsa, 1955 pieces and 13.4 GB size of each vertical camera axis images were collected in the case of the multicopter UAS survey. Their evaluation took 8 hours to process. In comparison, the 1052 pieces of images all having 9 GB size of the fixed-wing UAS can be processed in 1 hour on the same workstation. The average multicopter flight at this site lasted more than 1 hour and was accomplished with three take-offs. The fixed-wing UAS flight took on average 20 minutes with one take-off.

Among the study sites, an average of 1898 blind mole rat mounds were identified in the Blind mole rat Reserve of Hajdúbagos and an average of 1314 mounds in the grassland near Debrecen-Józsa.

In previously used traditional monitoring methods applying on-site field surveys, even very old mounds can be respectively clearly identified, nevertheless, these survey is intended to register the fresh mounds. Nevertheless, mounds older than a year have never been registered in the orthophotos. The orthophoto mosaics of the study sites characterised by sand and chernozem soils show only fresh mounds, which are a maximum of four months old. During the surveys, we found that in short-grass grazed grasslands, the high-resolution standardised orthophoto mosaic used in HRAMN provides the possibility for fast and satisfactory identification (over 85 % reliability), mapping, and counting of blind mole rat mounds. In addition, the geolocation of the mounds recorded on a standard orthophotograph is orders of magnitude more accurate than points recorded with a manual navigation device. The geometric accuracy of orthophotographs can range from 2 to 8 centimetres compared to 2–15 meters typical for handheld devices.

However, it should be pointed out that certain limiting factors occur in the blind mole rat habitats, which require field presence and control even with the UAS imagery-based HRAMN method. Such problematic areas requiring field operations include areas covered by tall vegetation, areas shared with other subterranean mammal species, and low-lying areas. The height and closure of herbaceous vegetation in some parts of the habitats (e.g., in low-lying parts) can make it difficult to identify the mounds. Such parts were observed in the case of the pasture near Debrecen-Józsa. In addition, blind mole rats sometimes make their mounds under bushes, which will not be visible in the aerial images. Although this question may seem insignificant, we found that in the Blind mole rat Reserve of Hajdúbagos, several solitary shrubs occur in the parts of the area inhabited by blind mole rats. The abundance of these bushes varies in different parts of the site. However, there are certain parts where blind mole rats are present and there is an average of one large shrub every 50–100 m. The blind mole rats prefer to make mounds in the shade of these (which is therefore not visible during aerial surveys), with an average of 1–3 mounds per bush. In some parts of most blind mole rat habitats, other subterranean mammal species (e.g., European mole, *Talpa europaea* or European water vole, *Arvicola amphibius*) also occur. We found that it could be difficult to distinguish the mounds of the different subterranean mammal species based solely on aerial photographs. In these problematic areas, additional on-site field monitoring is necessary, but our experiences show that the monitoring procedure based on HRAMN methodology reduces the area to be visited and the time required for on-site field surveys in blind mole rat habitats to a fraction of the time. Thus, the new approach can replace a full on-site field survey even in large areas of habitat and only requires additional fieldwork and validation.

During the survey, great attention was paid to using the method for determining the age of the mounds, however, it turned out that this problem requires further data collection, which was not the aim of the present study.

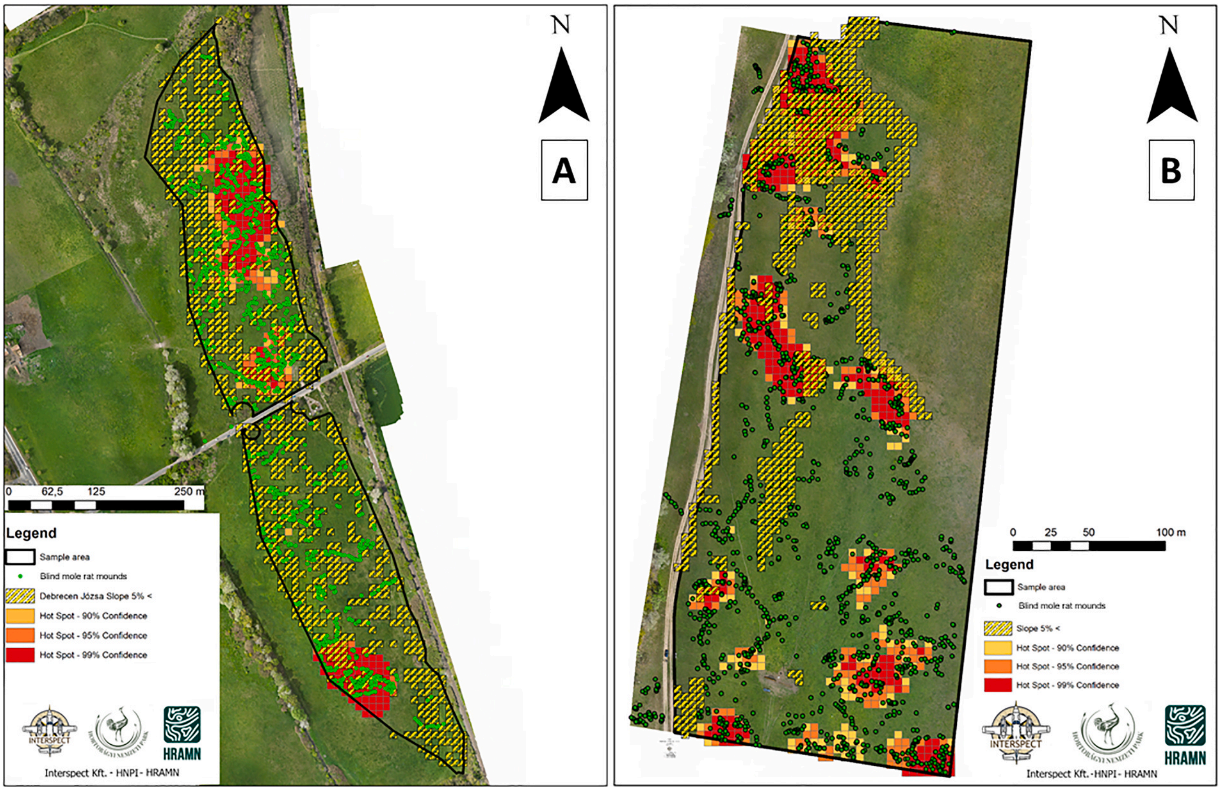

Fig. 2. The study sites near Debrecen-Józsa (**A**) and Hajdúbagos (**B**). The green dots are marks of the blind mole rat mounds. The HSA grinds signed with different coloured squares (90 % yellow, 95 % orange, and 99 % are red). The slopes greater than 5 % are also shown with light yellow hatched squares.

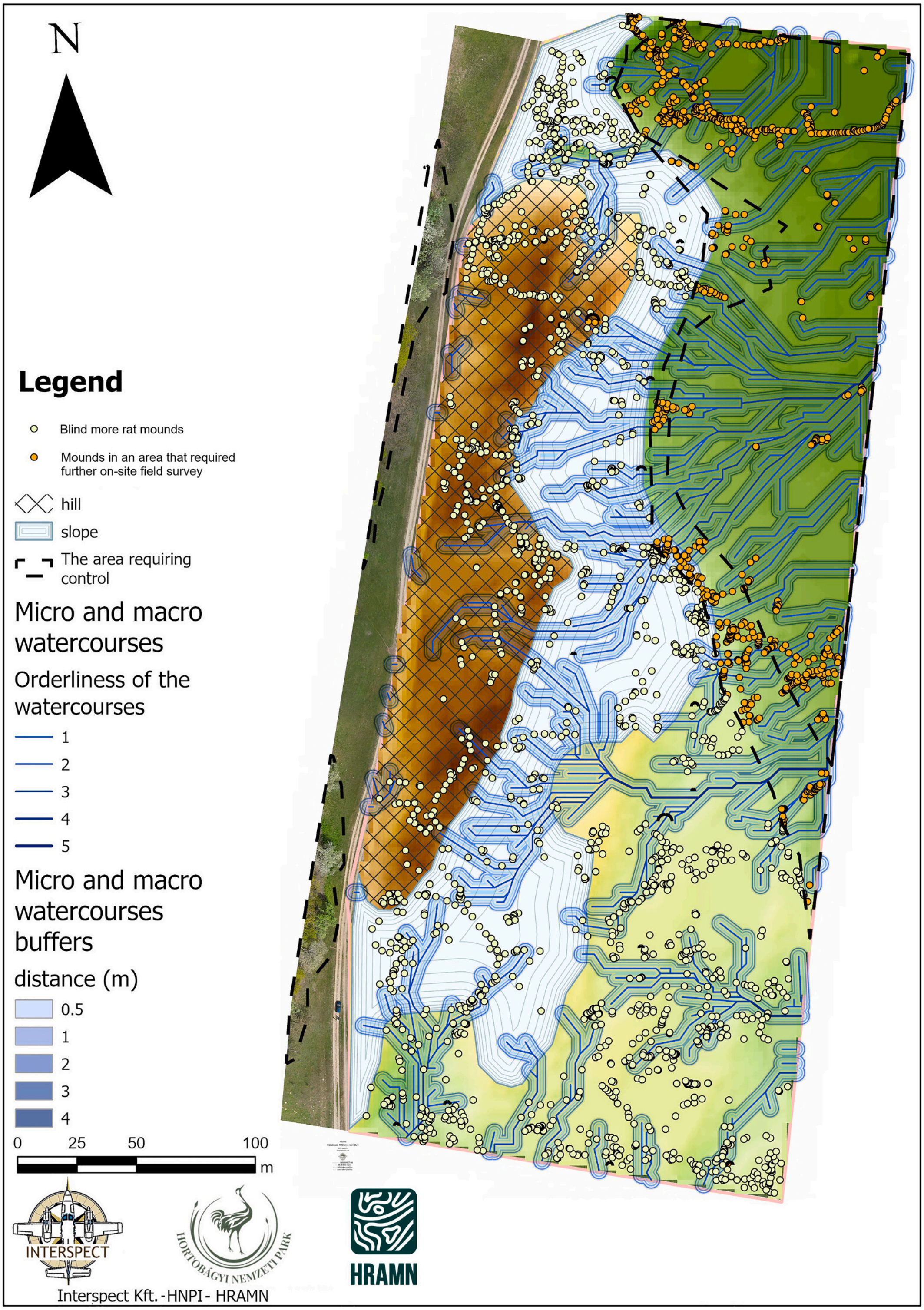

Fig. 3. Micro and macro watercourses compared to all the blind mole rat mounds in the study site near Hajdúbagos. The yellow dots are marks of the blind mole rat mounds. Orange dots indicate mounds that are located in areas inhabited by multiple subterranean mammal species. The changing colour of the map from brown to dark green indicates the relief and altitude above sea level. The blue lines and colouring are the representation of micro- and macro watercourses.

3.2. Spatial Pattern of blind mole rat mounds

In the Hot Spot Analysis (HSA), we used ArcGIS software to overlay the HSA 90 %-99 % square grids with slopes greater than 5 %. Our model showed one peak every 15 m when correlating with the slopes in our sample area of Hajdúbagos. At the same time, the map representation, clearly reveals that blind mole rat individuals prefer areas with a slope of less than 5 % (Fig. 2.). Thus, it seems that these subterranean rodents avoid or, if unavoidable for some reason, only temporarily use (for passage) areas with a slope steepness greater than 5 % and, if possible, do not make mounds on steep terrains. Only 9.8 % of the 1898 blind mole rat mounds in the study area near Hajdúbagos (Fig. 2.B) and only 4.6 % of the 1314 blind mole rat mounds in the study site near Debrecen-Józsa were on slopes steeper than 5 % (Fig. 2.A). Therefore, it was notable, particularly in the case of Debrecen-Józsa habitat that mounds were less frequent on steep slopes.

On sloping and hilly terrain along the drainage vectors of the rainwater collection models, within their two-meter radius, 78 % of the mounds in the study site near Debrecen-Józsa were formed. Only 23 % of mounds are located at lower altitudes, and here they avoid areas that flood during the rains. However, we see different numbers in the habitat of Hajdúbagos. In contrast, only 17.2 % of mounds were in a 2-m radius, but 36.56 % of the mounds were located in flat territories of lower elevation (Fig. 3.).

4. Discussion

4.1. Technical issues

HRAMN methodology can very well replace a full field survey to monitor blind mole rat habitats. Surveys with this can be particularly useful for the regular monitoring of the habitats of the blind mole rats of Central Europe.

Our results indicate that monitoring with HRAMN methodology could very well replace a full field survey of the habitats of *N. hungaricus hungaricus*. This proposed new method can be especially useful when monitoring large areas, for example, in the case of the habitat near Hajdúhadház, which is the home of the largest blind mole rat population in Hungary. There it is not physically feasible to carry out a full on-site field survey due to the size of the site. However, a survey with HRAMN methodology could be particularly useful for regular monitoring of that habitat.

Although the method was only applied to Hungarian blind mole rat habitats in the present study, we consider that it may be suitable for surveying any Central European blind mole rat habitat, regardless of the blind mole rat species inhabiting them (Fig. 1B). Moreover, we assume that it could be appropriate for a fast and accurate survey of blind mole rats populations of any habitat and any species within the entire range of the Spalacinae subfamily. However, further studies are needed to identify factors that limit the reliability of the survey in other geographical regions. It is also possible that the method could be used to monitor populations of other subterranean mammal species, but further studies are undoubtedly needed to confirm the applicability of the method and to identify limiting factors of reliability.

As described in detail in Section 2.2, surveys using the HRAMN methodology can be categorised into missions using multirotor drones and fixed-wing aircraft to optimise the cost and time expenditure of the survey. Areas smaller than 60 ha that cannot be combined with nearby habitats into a single flight campaign should be surveyed using multirotor UAS. Larger habitats that can be surveyed collectively or as a group are best surveyed using fixed-wing UAS. The habitats of other more threatened species of blind mole rats (e.g., Vojvodina blind mole rat and Srem blind mole rat) in the Pannonian Basin (Csorba et al., 2023) could be effectively monitored using the same method described in this paper. This would provide important information that could be used for the effective conservation of these endangered and rare species. For examining all known blind mole rat habitats of the Pannonian Basin (see Fig. 1.B), the fastest approach is to conduct 22 fixed-wing UAS and 4 multirotor UAS deployments per period. This would make it possible to complete a survey of all habitats within 60 days with the accuracy of geodetic measurements.

However, the identified limiting factors will need to be further investigated in subsequent studies. The following recommendations can be made:

The tall-vegetation-covered parts of the blind mole rat habitat near Debrecen-Józsa are mown, thus the height of the vegetation and the time of mowing are decisive. In this case, it is advisable to time the survey immediately after mowing, and if it is possible, to remove the hay from the site as soon as possible, the proportion of the territory that can be mapped based on aerial surveys can be maximized. In this case, even mowed mounds leave a vegetation-free ground surface, from which it can be identified in the orthophoto mosaic that it was a mound.

Scattered shrubs, under which blind mole rat mounds may occur, are not detectable during aerial surveys. Therefore, these sites should be visited separately as a part of an on-site field survey during the recording period, and mounds that are potentially missing from the aerial recording must be recorded by a manual device. Points saved with a manual navigation device can be opened on the standard orthophoto and aligned to their true geographic location with a 15–20 cm accuracy. In certain parts of other blind mole rat habitats in Hungary, which are not covered by the surveys presented in this publication, the density of shrubs may be even higher however, blind mole rats are still presented. These represent an unfavourable situation from the conservation point of view, but in some cases, the conservation authorities and managers may struggle to act effectively against it. Therefore, managing this issue could be important for monitoring blind mole rat populations.

With regard to the difficulties caused by the presence of other subterranean mammal species, it should be mentioned that, in theory, the mounds of all three species could be distinguished from orthophotos as well. Blind mole rats are more inclined to make lines of mounds, whereas moles are more likely to make clusters of mounds (Moldován et al., 2021). Additionally, blind mole rats and water voles differ in their habitat use, as blind mole rats usually use the dry habitats of the higher elevations of the sites (Horváth et al., 2007), while water voles prefer the lowest parts with wet meadow habitats (Horváth, 2007). However, numerous field experiences indicate that the identification of these species within a specific site can be respectively challenging (Moldován et al., 2021, Schneider et al., 2022). To manage these difficulties a preliminary field survey should be carried out to determine, which parts of the site are likely to contain other species. These areas need to be checked by on-site field inspection following the UAV survey. Aerial mensuration is suitable for assessing parts that are solely inhabited by blind mole rats. This can save a large amount of time and effort. Certain known parts of the investigated habitats (e.g., low elevation parts) where other species occur more frequently or where the vegetation is different, and this makes it more difficult to identify the mounds from the images. These areas can be pre-screened by the topography and vegetation map also available during HRAMN surveys and can be selected for on-site field control as a complement to the aerial survey.

Since orthophotos do not show any mounds older than a few months, our method may be a proper way to record objectively only blind mole rat individuals that were active at the time of the survey. This also allows for avoiding registering the mounds of individuals who may have died and are no longer part of the population.

However, determining the proper age of the mounds is not a simple task even during the traditional on-site field survey method as there is no suitable reference or protocol for age determination. Many different factors may influence the morphological changes of the mounds, such as soil characteristics, or weather conditions (rainfall, wind) of the period before the fieldwork (Moldován et al., 2021). What can be a clue is the structure of the surface of the mounds, the height of the mounds, and the vegetation growing out from under the soil of the mounds or newly on the surface. However, it turned out that these cannot be reliably identified from aerial photographs. Thus, a comparison of digitised datasets based on aerial photographs of the same area taken at sufficiently frequent intervals can help to investigate the temporal dynamics of changes in the mounds. This will also require the development of an appropriate geo-informatics target software, which is one of the authors' future research goals. This method could also provide an almost instantaneous picture of the fresh mounds, which could be important in documenting new lines of mounds that develop over a few days.

4.2. Habitat use of blind mole rats

In reality, this distance means that the different individuals are located within a radius of about 15 m from each other, thus forming the HSAs. Interestingly, this distance has been found previously using various attempts as a size of an average blind mole rat territory in habitats of the Pannonian Basin characterised by sandy soils (Mikes et al., 1982, Moldován et al., 2021).

In the case of the Pannonian Basin endemic subspecies of Hungarian blind mole rat (*N. hungaricus hungaricus*), in average years, after a period of reduced summer excavation activity, mounds building and development of the tunnels starts with the first autumn rains (Moldován, 2014). It was previously assumed that this is because the soil is more stable at this time than in dry periods and therefore less likely to collapse during the construction of the tunnels (Horváth et al., 2007). A general strategy of subterranean mammals is to increase tunnelling activity in the rainy season when soil is softer and easier to dig, and therefore digging is energetically less demanding and plant material is also more abundant (Heth, 1989, Zuri and Terkel, 1997, Vaughan, 1962). However, it has been proven that certain subterranean species dig in the hard summer soil, and rather than pushing soil above the ground at a high-energy cost, they push it into abandoned tunnels (Genelly, 1965, Lovegrove and Painting, 1987). Many studies reveal soil water content is a major factor affecting the digging activity of subterranean mammals; the tunnelling activity is influenced by soil moisture (Collis-George, 1959, Miller, 1948, Nevo, 1961, Zuri and Terkel, 1997). Our findings resulting from the geo-informatics approach also support this idea. The fact that the blind mole rat mounds line up along the drainage vectors of the rainwater collection models suggests that the individuals on slopes and hillslopes take advantage of the soil strips moistened by the downstream rainwater runoff during rainfall. Similarly, it was found in Israel in the case of a population of Mount Carmel blind mole rats (*N. carmeli* Nevo, Ivanitskaya and Bailes, 2001) near Tel-Aviv (Zuri and Terkel, 1997). If they have the opportunity, they advance in these areas, because in these parts, the soil can be shaped for a longer time than on the hillsides, and the stability of the soil is maintained longer than in the surrounding areas (Fig. 3). There are also periods when the level of moisture in these bands already inhibits them. The stability of the soil is increased after rain, but it is demonstrable that long-term areas with stagnant water are avoided during the construction of the tunnels. At the same time, all these close relationships raise the question of whether the Hungarian blind mole rat can be considered an ecosystem engineer species. It is questionable whether we are seeing rainwater collection vectors influenced by the topography or a rainwater runoff system strengthened or possibly transformed by the created blind mole rat mounds. Understanding this question requires further thorough investigations, studying the relationship between the mounds that appeared at different times and the meantime changes in the rainwater collection system.

5. Conclusion

Blind mole rats are among the most endangered mammals of the Central European grasslands. Recent research has shown not only that the species richness of the group has been seriously underestimated (Németh et al., 2024), but also that many of the recently identified species are highly endangered (Csorba et al., 2023). Thus, regular monitoring of their population changes is an especially important task. Although various efforts to monitor populations have been made for a long time, a truly effective method for monitoring any population in the region has not yet been developed (Moldován et al., 2021, Schneider et al., 2022). The largest habitats, which are of particular importance for the survival of the species, for example, cannot be monitored using the extensive field survey method (Moldován et al., 2021) used so far, as it would require time and resources that cannot be provided by national parks in Central Europe. However, with the here presented method, these populations can be systematically surveyed (Fig. 1.B, 1.D). This is very important because a sufficient number and regularity of monitoring data is needed to distinguish natural dynamics from changes that indicate harmful processes in the population. These are currently not available. A further problem is that global climate change has resulted in a succession of virtually extreme years over the last decades (Boergens et al., 2020, C3S, 2022, Lakatos et al., 2013), therefore very large amounts of monitoring data would be needed to correctly assess the effects of each extreme year on the populations. The method presented here not only saves time and effort but also allows larger areas to be surveyed within a given period. With more monitoring data available, besides the previously mentioned problems, the geomorphological and soil conditions preferred by blind mole rats will be better understood, allowing their movements and land use to be modelled. Our future goals include studying this in more depth and with greater precision. From a future research perspective the transformation and drying of low-lying areas, which were previously even wetter habitats, due to climatic changes is of great interest. Blind mole rats living exclusively in dry habitats will eventually use these areas and this can be confirmed by a long-term, systematic sufficiently frequent monitoring survey. However, such low-lying areas can quickly fill up with water due to variable climate and unpredictable weather events and therefore carry a higher risk for blind mole rat conservation in the future.

Thus, by using our proposed monitoring method, we will obtain significantly more data on the spatial and temporal activity of blind mole rats in their different habitats. These data will help us to better understand the behaviour and biology of these endangered mammals (e.g. their ecological role in their habitat) and will also provide an enormous database for their effective practical conservation. The data will be stored in the databases of the national park authorities and the HRAMN, making them freely accessible to researchers and conservation professionals.

Ethics statement

Not applicable: This manuscript does not include human or animal research.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

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