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RESEARCH ARTICLE

UAV-based aerial imagery to identify high quality habitats for the endangered Bog Fritillary butterfly

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Abstract
Context Land use intensification has led to a reduction of valuable open habitats over the past decades. The remaining habitats are mostly small and geographically isolated from each other. Bogs and wetland habitats have suffered particularly strongly under habitat destruction and reduction of habitat quality. The Bog Fritillary butterfly *Boloria eunomia* occurs on little-used wet meadows and bogs, and exists today mostly in small remnant populations in Central Europe.
Objective In this study, we investigate the population ecology and habitat demands of the highly endangered *B. eunomia* for a remnant population and the surrounding landscape in Northern Austria.
Methods We combined habitat parameters collected on the ground with data derived from UAV-imagery and with Mark-Release-Recapture data.
Results Our study shows that the population studied is very small and that individuals behave highly sedentary. Habitat suitability depends on the occurrence of *Bistorta officinalis*, the butterfly´s single larval food plant, and the availability of a strong litter layer. UAV-based orthophotos enable the identification of further potential habitats for this butterfly species at a landscape level.
Conclusions Our study confirms that *B. eunomia* has very specific habitat requirements. With airborne data it is possible to identify potentially suitable habitats on a landscape level and thus find further potential habitats for this rare butterfly species. Intensive land management with frequent mowing and the drainage of wet meadows leads to the disappearance of such highly specialized species.

Keywords Butterfly conservation · Mark-Release-Recapture · Habitat parameters · High-resolution aerial pictures · Drone · Habitat suitability · Population ecology · *Boloria eunomia*

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Introduction

Land use intensification has led to the destruction of numerous natural and semi-natural habitats across Central Europe (Raven and Wagner 2021; Shipley et al. 2024). As a result, today, numerous ecosystems are small and isolated such as bogs and wetlands (Lindner and Hobohm 2021). Habitat quality of such habitats becomes often negatively affected by drainage, melioration or the influx of nitrogen and pesticides (Dollar et al. 2013; Guariento et al. 2023). Subsequently this impacts flora and fauna existing on such sites (Maskell et al. 2019; Bottero et al. 2023; Klein et al. 2023).

Species that rely on very specific habitat structures and resources suffer particularly under changes and the deterioration of habitat quality (Dennis and Eales 1997; Warren et al. 2021; Graser et al. 2023). Such species exist today frequently in small and isolated populations and suffer under demographic and environmental stochasticity (Melbourne and Hastings 2008; Pertoldi et al. 2021), as well as under genetic inbreeding (DiLeo et al. 2024). This might affect population vitality and persistence and underlines the relevance to combine analyses on the population structure, behaviour and habitat use of selected target species. Not only the habitat in question, but also the entire surrounding landscape should be taken into account.

Mark-Release-Recapture (MRR) provides valuable information on the population ecology of a species, including behaviour and habitat preference (Turlure et al. 2018; Habel et al. 2023). These data can be combined with habitat parameters, such as microhabitat structures, microclimate and vegetation (Habel et al. 2023). As MRR relies on single locations of occurrence, the matrix in between different re-/capture sites mostly remains unknown or has to be characterized by time consuming ground surveys. The combination of different spatial scales to investigate potentially suitable habitats in between abundance locations and potential migration routes or barriers can be achieved by remote sensing approaches (Weiers et al. 2004; Nagendra et al. 2013; Alvarez-Vanhard et al. 2021). High-resolution aerial images taken by drones can cover adjacent areas and deliver valuable environmental information (Alvarez-Vanhard et al. 2020; Dietenberger et al. 2025).

In this study, we analyse population ecology and habitat demands of the highly endangered Bog Fritillary butterfly, *Boloria eunomia*. This is a boreo-montane butterfly species that can be found in wet meadows (Turlure et al. 2011). Caterpillars of this butterfly species feeds exclusively on *Bistorta officinalis* and still occurs in little used wet meadows (Turlure et al. 2011). Land use intensification caused the drainage of wet meadows, and many wetlands have been afforested and thus wet meadows became very scarce over major parts of Europe (Lindner and Hobohm 2021). In addition, caterpillar respond highly sensitive to habitat disturbances (non-adapted mowing) and changes of microhabitat structures of the habitat (Baguette et al. 2011; Radchuk et al. 2013). In consequence, most remaining populations of this butterfly are small and geographically isolated (De Vries and Van Swaay 2009).

Here, we captured, marked and re-captured individuals of *B. eunomia* during two flight periods (2023 and 2024) to study the population structure and movement. In parallel, we recorded habitat structures, microclimate and vegetation composition in the habitat and in the surrounding landscape. Landcover and relief information were assessed on the basis of high-resolution aerial photographs taken with an Unmanned Aerial Vehicle (UAV) (Koh and Wich 2012; Díaz-Varela et al. 2018). Based on these data we evaluated the status and behaviour of this local population. We will screen the surrounding environment for potentially suitable habitats, and will translate these findings into habitat- and species management. We will elaborate on the following questions:

1. What is the size and structure of the population under investigation, and how mobile are the individuals?
2. Which factors determine the species´ habitat suitability?
3. Do potentially suitable habitats exist in the immediate vicinity?
4. What added value is created by combining the micro-habitat and landscape level?
5. What consequences can be derived from our results for the management and protection of this butterfly species and the entire ecosystem?

Material and methods

Study species

The Bog Fritillary butterfly, *Boloria eunomia* relies on still intact bogs and little used wet meadows (Turlure et al. 2011). The species shows a boreo-montane distribution, with main occurrences in Asia and North America (Tuzov and Bozano 2021). The species occurs in Central Europe mainly in distinct populations at the northern foothills of the Alps at higher altitudes (Gros and Hauser 2014), in the Middle Mountains from the Balkans to the Pyrenees (Maresova et al. 2019; Nève et al. 2000), and in parts of Fennoscandia (Maresova et al. 2019). The butterfly larvae feeds exclusively on *Bistorta officinalis* (Maresova et al. 2019). *Boloria eunomia* is on the wing in one generation from mid-May to end of June (Settele 2025; Sing et al. 2024). Females are largely sedentary, whereas males patrol sunlit sections of the meadow; mating usually follows immediately after female imago emergence (Turlure et al. 2011; Blomfield 2021). The lifespan of the animals is usually limited to a few days (Settele 2025). Eggs are laid as small egg clutches, on the underside of *B. officinalis* leafs. The larvae overwinters in the second larval stage in the wilted leaves of the host plant, or hidden in the litter (Düring 2023). Due to specific habitat requirements, this butterfly species underwent a dramatic decline across major parts of Central Europe, and thus is classified as critically endangered for most parts of Central Europe (Huemer et al. 2022; Gros 2023), and as endangered for Austria (Höttinger and Pennerstorfer 2005).

Study area

Our study area is located in northern Austria (Lengau, Braunau am Inn district, federal state of Upper Austria), at an altitude of 495 m asl. The climate is temperate, with summer highs of around 30 °C and winter lows of around − 5 °C (Merkel 2022). The local habitat of *B. eunomia* is restricted to a section of about 1600 m^2 (minimum geometry of the occurrence points of *B. eunomia*, Fig. 1) and is characterized by a high density of *Bistorta officinalis*. This grassland section was fallow land until the year 2015. In the following, this grassland was split into two equally sized parts, which were mown alternately (one section mown during end of September, the other half without mowing, and vice versa in the subsequent year). There was no fertilization and no pesticide applications. This management was carried out explicitly for the conservation of this butterfly species. The surrounding grasslands were mown twice a year, drained by ditches, and organic and artificial fertilizers were used. The nearest population of *B. eunomia* is about 40 km distant (wetlands of Blinklingmoos, Strobl).

Mark-Release-Recapture

Mark-release-recapture was conducted along a path, which covered the main habitat and the surrounding environment in our study area (Fig. 1). For each individual we noted date of capture and time, sex of the butterfly and weather conditions. Individuals were marked with a running number on the underside of the hindwing, using a waterproof pen. Each observation point was measured with a hand-held GPS device (Garmin GPSMap 65). Observations were conducted covering the main flight period of *B. eunomia* (27.5.-12.6.2023, 21.5.-6.6.2024). Data were collected between 9 a.m. and 5 p.m. under suitable weather conditions (sunny, about 20 °C).

Habitat parameters

Microclimate and habitat structures significantly impact flora and fauna (Stoutjesdijk and Barkman 2014; Scherer and Fartmann 2022). Therefore, biotic and abiotic parameters were recorded on 77 study plots (1 m^2 each) spread across the study area (Fig. 1). We recorded microclimate (temperature, humidity) with climate loggers (DK320 ruggedPlus HumiLog) over a period of 2 months (May and June 2023). Plant species were identified for each plot and their cover was estimated on an ordinal scale according to Braun-Blanquet. To detect the biotic and abiotic situation of the corresponding location, Ellenberg indicator values were compiled for the recorded plant species and summarized per plot with a weighted mean according to the Braun-Blanquet categories (r = 0, + = 0.1, 1 = 2.5, 2 = 15, 3 = 37.5, 4 = 62.5, 5 = 87.5) (see Ellenberg et al. 1991). We recorded sociability (individual plants or group growth) in relation to the square meter area based on Braun-Blanquet method (for details see Kent 2012). We further assessed the following structural parameters per plot: Bare soil (percent coverage), vegetation height (cm), proportion of litter cover (%), vegetation density (low, medium, high), proportion of moss (%), and number of inflorescences, separated by yellow and violet (the relevant colours for butterfly which might influence the visits and thus occurrence of butterfly taxa, see Tiple et al. 2006).

Fig. 1 Study area in Austria (star in small inlet map), and the grassland sites studied. Given are the 77 study plots (with triangles) and the path (white line) established for observing and collecting individuals of *Boloria eunomia*. Occurrences of the butterfly species are shown as squares. Italic numbers within the black outlined grassland plots are respective parcel numbers. Coloured background data shows calculated orthomosaic based on UAV imagery from 2023

All raw data are given as electronic supplementary material, in appendix 1.

High-resolution aerial images

High-resolution aerial images were taken from a DJI Matrice 300 RTK drone and the MicaSense RedEdge MX-Dual camera system. This Unmanned Aerial Vehicle (UAV) is a multicopter with very precise positioning using Real Time Kinematic (RTK). The attached camera system records 10 bands and as a multispectral camera system these bands are aligned according to common satellite products (e.g. LANDSAT or SENTINEL 2 mission) to ease upscaling to coarser scales of very high resolution multispectral imagery with the help of public available satellite products (Zabala 2017). The benefits of using the UAV system are higher geometric resolution, greater flexibility of acquisition times compared to satellite products, and lesser disturbance through cloud coverage (as flight height is restricted to 120 m above ground) (Alvarez-Vanhard et al. 2020; Slade et al. 2023). UAV-based aerial images were taken on the 31.5.2023, the main flowering period of *B. officinalis* and flight time of *B. eunomia*. As the flowers are comparatively small and often located close to small ditches, the acquisition of aerial images for orthomapping and elevation modelling taken from UAV is essential and more cost-efficient compared to commercial satellite imagery. The flights were conducted at 50 m above ground with single manual acquisition of images covering MicaSense calibration panel before and after each flight. This gives us aerial images with geometric resolution of 5 cm. The camera's channels cover the following sections of the electromagnetic spectrum (corresponding section widths are given in parentheses): Coastal blue 444(28)nm, Blue 475(32) nm, Green 531(14) nm, Green 560(27) nm, Red 650(16) nm, Red 668(14) nm, Red Edge 705(10) nm, Red Edge 717(12) nm, Red Edge 740(18) nm and NIR 842(57) nm. The camera system was configured with an overlap of 80% to the previous images, in between flight lines and was always maintained during the flight. This is the prerequisite for calculating a large orthomosaic (Agisoft LLC 2024). Processing of acquired imagery was done using Agisoft Metashape Professional v.1.8.3 with "high quality" settings (Agisoft LLC 2024) and prior reflectance calibration using MicaSense delivered reflectance calibration panel, resulting in a 10-band orthomosaic and digital surface model covering the study area.

Statistics

Mark-Release-Recapture

Data on captures and recaptures from the years 2023 and 2024 were used to analyse the mobility of individuals. The data were processed using R 4.4.2 (R Core Team 2024). Spatial analyses were carried out with the package sf (Pebesma 2018) using the MGI/Austria Lambert (EPSG: 31287) coordinate reference system. For individuals that were recorded multiple times, distances between the first and second capture were then calculated. A Welch Two-sample t-test on the logarithm of these distances was used to test for differences in mobility between sexes. A measure of life-span was obtained by the time difference between first and last capture.

Habitat suitability model

Habitat suitability models were calculated on the basis of the ten-colour-band high-resolution aerial orthomosaic dataset taken with the MicaSense Red-Edge MX dual camera in 2023. Only specimen records from 2023 were used since vegetation cover might differ between years. The aerial images were used to calculate a digital surface model (DSM) as well as the normalized difference vegetation index (NDVI = (NIR—Red)/(NIR + Red)) (Huang et al. 2021). These variables are suitable to describe the general surface cover and its spatial structure as well as to distinguish different vegetation types. In addition, multicolinearity and dimensionality of the 10-colour-band orthomosaic was reduced by principal component analysis. The number of principal components to retain was based on a scree plot. The habitat suitability model (HSM) was inferred with Maxent using megaSDM (Shipley et al. 2022) as a frontend. Two principal components, the DSM and the NDVI served as predictors in the HSM. Background data were created with megaSDM. To mitigate sampling bias, environmental subsampling (Varela et al. 2014) was applied for background points and 60% of the points were sampled within a buffer of 10 m around presence points. The median prediction per pixel of four replicate Maxent models was projected to the study area to reduce the impact of outliers and to ensure high accuracy. In addition, binary maps were calculated based on the maximum sensitivity plus specificity criterion as implemented in Maxent.

Further investigation of the relevance of specific habitat parameters for *B. eunomia* was based on the binary presence-absence map projections of the HSM and the habitat parameters that were recorded at the plots. Therefore, we created 1 m^2 squares around each plot with terra and sp. In addition to the habitat parameters (see above), we also considered the abiotic conditions such as temperature and humidity collected with climate-loggers plot-wise. We imported the squares into QGIS 3.16.4 (QGIS Development Team 2020) and calculated the percentage of presence and absence pixels within the squares. Plots with more than 50% presence pixels were considered suitable for *B. eunomia*. Others were considered unsuitable in the following. Habitat parameter values of suitable and unsuitable plots were then tested for significant differences using a Welch Two sample t-test (Welch 1938). Results were visualized with ggplot2 (Wickham 2016).

Results

Mark-Release-Recapture

In total, 46 individuals were recorded, 32 in 2023 (25 males, 7 females), and 14 in 2024 (2 males, 12 females). The mean lifespan was calculated as the average of the recaptures for 2023 and 2024 and was 1.8 days and 4.0 days, respectively. The maximum life span was nine days and the minimum life span was one day. The mean flight distance of individuals from both years was 10.1 m. The mean flight distance of females was 13.0 m (of 11 recaptures), that of males was 7.5 m (of 12 recaptures). Males and females showed no significant differences in flight distances.

Habitat suitability models

The average area under the receiver operator characteristic curve (ROC-AUC) for the replicate runs was 0.84. Average percentage contribution of predictors across replicates was PC2 = 41.8%, NDVI = 37.0%, PC1 = 12.2%, and DSM = 9.0%. Based on Maxent's jackknife test of variable importance in the training data, PC2—closely followed by NDVI—had the highest information content per se. The NDVI had the most information content that was not present in other variables.

The HSM suggested that the area where the majority of individuals was captured was a suitable habitat, while surrounding areas and some ditches also appeared to be potentially suitable. However, only a limited part of the area, particularly along the small ditches that extend from southeast to northwest, especially in the center and western part of the area, were classified as suitable (Fig. 2).

We found significant differences between suitable and unsuitable habitats for the litter height, based on the Welch t-test ($p < 0.01$) (between suitable (36.82 cm) and unsuitable habitats (16.09 cm)). For all other parameters assessed we found no significant difference: Shade, flower (total), flower (yellow blossoms), flower (purple), Ellenberg indicator values (humidity, continentality, light, nutrient, reaction). Also for the microclimatic conditions we found no significant differences (temperature, frequency humidity high, frequency humidity low, frequency temperature high, frequency temperature low, humidity maximum, humidity minimum, humidity average, humidity average daily, humidity standard deviation, humidity span, average temperature fluctuation, temperature maximum, temperature minimum, temperature average, temperature standard deviation, temperature span). And. Also further habitat parameters did not reveal significant values between occupied and non-occupied sites, as observed for moss cover, bare soil, litter cover, litter height, vegetation density, vegetation height.

Discussion

Population ecology and behaviour

Our results show that the local population size of *B. eunomia* is very small and the mean lifespan is a few days only. We observed highly restricted movement behaviour for this butterfly species. This contrasts with previous findings. Studies on the dispersal behaviour of *B. eunomia* evidenced strong colonisation power, indicated for populations in Western Europe (Nève et al. 1996) and Central Europe (Nève et al. 2009). There are different potential explanations for this strongly diverging result out of our study. The feature obtained for our population and study site might be a warning signal of being a population at the brink of extinction (Van Noordwijk 1994). The population might suffer under genetic inbreeding and subsequent reduced life-span and little flight power (Saccheri et al. 1998; Pignataro et al. 2023). According to Nève et al. (2008), *B. eunomia* shows rather restricted dispersal in plains if compared with populations located in mountainous areas. As our study area is situated in a highly anthropogenic and flat valley, both factors might affect the movement behavior of the species (see also Vandewoestijne and Baguette 2004). Another possible explanation for the restricted flight distances found in our study could also be caused by a too limited investigation area (typical for MRR studies, see Lindberg 2012).

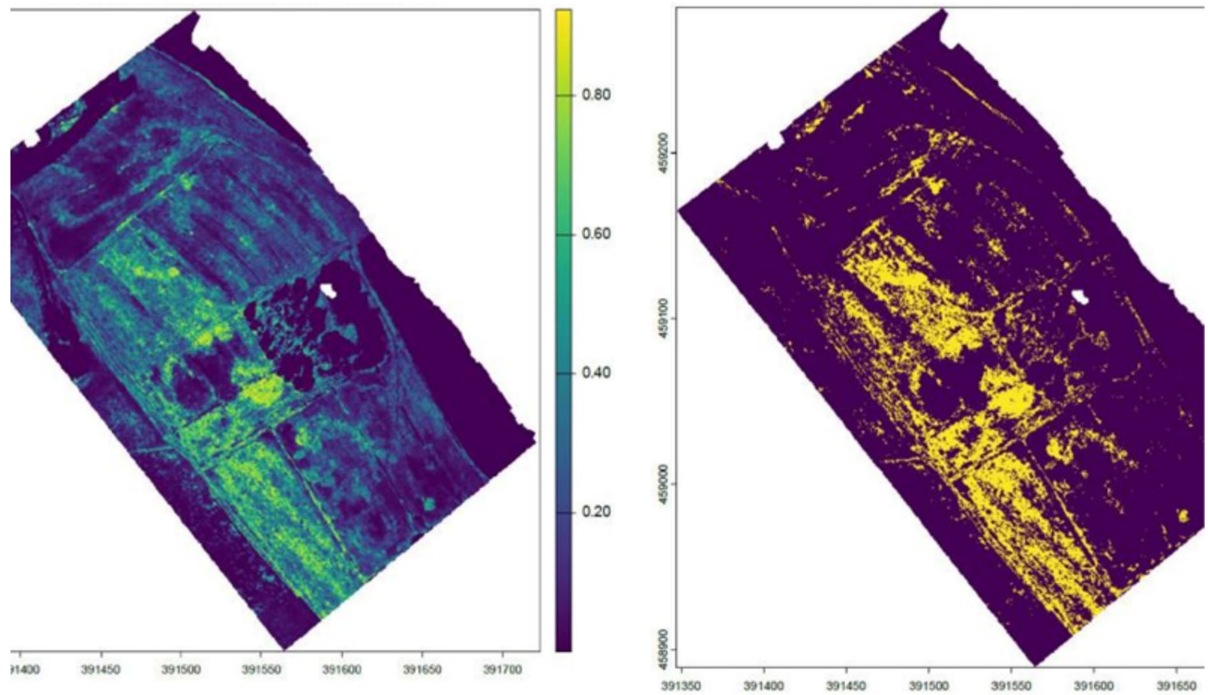

Fig. 2 Habitat suitability model indicating potentially suitable habitats of *B. eunomia*, based on a high resolution orthomosaic, and the parameters derived from (topography, NDVI), and ground-truthing data. Left = habitat suitability model, continuous, right = habitat suitability model, binary (yellow = suitable, dark = not suitable)

In order to avoid this, a fairly large area with the observation path was established. Thus, it would have been possible with our observation tours to take into account individuals that also cover greater distances. However, potential habitats that are actually further away were not taken into account in this study.

The very restricted mobility observed for *B. eunomia* in combination with the strongly isolated habitat remnant let us assume that there is no population network existing. This situation in addition lowers the likelihood of persistence of this local butterfly population. The degree of ecological specialisation (e.g. habitat demands, larval food plants) frequently goes in line with comparatively little dispersal, as shown for the Karner Blue Butterfly *Lycaeides melissa samuelis* (Chau et al. 2020). This lack of a potential habitat network and subsequent population persistence of respective taxa becomes further aggravated through continuing habitat destruction and subsequent rising habitat fragmentation (Chau et al. 2020; Suárez et al. 2022). Such a trend could also have a negative impact on the persistence of *B. eunomia*.

Habitat suitability from microhabitat to landscape level

Our habitat suitability models illustrate that most individuals of *B. eunomia* occur restricted to sites which are also characterized by high habitat suitability according to our modelling predictions. Hereby, the main explaining variables is high density of its larval food plant (*B. officinalis*) and the availability of litter. This goes in line with previous studies on the habitat demands of *B. eunomia* in other parts of Central Europe (Turlure et al. 2019; Chau et al. 2020). This butterfly rely on semi-successional habitat stages of open wetlands, with low mowing frequency (Turlure et al. 2011). In consequence, high farming intensity negatively impacts the degree of habitat suitability for *B. eunomia*. For example, grasslands that has been fertilized intensively with manure (e.g. cadastral parcel 1538/1) do not represent potential habitats for the butterfly species. Intense fertilization accelerates growth rates and thus increases vegetation height and density, and reduces plant species diversity (and fauna) (Hilpold et al. 2018). Neighbouring grassland sites in our study area (e.g. parcel 1536/1 and 1537/1) are fertilized only organically and show some spots which might be suitable for successful development of *B. eunomia*.

Especially cadastral parcel 1531, which is only mowed once a year and not fertilized also has promising areas along its ditches that could serve as habitat for the butterfly species. This might be even a suitable habitat if management intensity becomes further reduced (Konvicka et al. 2023). The habitat patch (parcel 1537/2), where most of the individuals of *B. eunomia* were caught, is extensively farmed and contains both suitable habitat areas and valuable ditches. These structures provide valuable nectar sources and larval habitats, as they often contain diverse vegetation that is lacking in intensively farmed and frequently mown areas. In addition, some of the humid ditches create linear structures of high habitat suitability. These ditches are more humid and its management are rather sporadic. This creates preconditions for successful development of *B. eunomia* (Turlure et al. 2019).

Most of the parameters on microhabitat structures assessed on the plots were quite similar on the different plots (vegetation, structures). Only the presence of litter and the litter cover differed between the areas where *B. eunomia* occurs and the other areas. We found that the mean litter height is higher in suitable habitats compared to non-suitable habitat sites. This difference indicates the importance of litter height for the survival of the species, especially for the hibernating caterpillars. The study by Karban et al. (2017) shows that litter offers a suitable microhabitat for many butterfly larvae with effective protection from predators such as ants. Caterpillars had higher survival rates at locations with more litter. Protection by the litter layer results from the fact that it provides a physical hiding place and protects the caterpillars from direct contact with predators. Even when litter was moved from moist locations to dry habitats, this protective effect remained (Karban et al. 2017). These results underline the importance of the litter layer as a protective element in habitats, especially for species that are endangered by ground predators (Karban et al. 2017). Our data and previous work underlines the relevance of microhabitat conditions being of key-relevance for successful larval development and the persistence of species (Kruse et al. 2016).

The results obtained make it clear that with the help of high-resolution aerial photographs it is possible to identify areas on micro-scale within the study areas and covering larger parts in the landscape that definitely have potential for a species and should therefore be used first in a restoration (Habel et al. 2016). Furthermore, very high-resolution data from UAV allow for analysis of fragmentation and patch pattern on a micro-scale and deliver ecological relevant information in more fine resolution than medium to high resolution satellite data (Villarreal et al. 2025). Our study also shows that with modern technology it is possible to consider microhabitat parameters and habitat structures even at a landscape scale. Here, UAV-derived data can better provide training and validation data for habitat modelling approaches at the necessary precision and level of detail than pure satellite data can (Alvarez-Vanhard et al. 2020). UAV-derived habitat parameter can reduce the gap between time-consuming and cost-inefficient ground surveys and available but coarse satellite products and thus spatial scales can be bridged with higher flexibility and necessary level of detail.

Conservation implications

The current habitat should be expanded by a reduction of the mowing frequency (only during late autumn) (Kasiske et al. 2024), no use of fertilizer, and the creation of partial fallow lands. The adjacent areas, which already have quite good habitat quality for this species, could be considered for this purpose. The adjacent area (eastwards), which has been afforested some time ago, should be deforested and restored into a wet meadow. Ditches also indicate a comparatively high habitat suitability and could therefore serve as valuable corridors and potential small habitats for this threatened butterfly species. For efficient protection and medium-term conservation of this species the entire landscape have to be taken into consideration. Studies have shown that even intensive and adapted management in isolated protected areas can only preserve species diversity for a short time (Habel et al. 2016). The use of drones and other approaches from the field of remote sensing makes it possible to identify and restore potential habitats across larger spatial scales.

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Declarations

Competing interests The authors declare no competing interests.

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