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LEPMON: Recording the biodiversity of moths (Lepidoptera) with automated cameras and artificial intelligence

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Reviewable v 1

Abstract

Monitoring insect populations has become an urgent priority given the ongoing biodiversity crisis, and the resulting changes to ecosystem services. However, the available data on insect population trends are severely limited in terms of taxonomic, spatial, and temporal resolution, due to the time-consuming nature of insect collection and identification. The goal of LEPMON (LEPidoptera MONitoring) is to develop a powerful, stable and scalable automated nocturnal insect recording system for long-term monitoring and answering ecological questions. The project runs from December 2024 to November 2027. We provide an overview of the entire project, summarizing the original research proposal and current developments as of August 2026. LEPMON uses time-lapse digital photography of nocturnal insects attracted to a white screen using UV light (LepiLED) with a high resolution of 16 px/mm. Artificial intelligence (AI) is applied for automated processing of the collected images. The recording system comprises two different models of Automated Recorders for Nocturnal Insects (ARNIs). The ARNI-Pro is the high-end model with the highest image quality and durable components, designed for professional users. ARNI-CS is the more affordable and portable alternative with slightly reduced image quality, built largely using 3D-printed components. As of August 2026, 67 ARNI-Pros and 34 ARNI-CS's have been installed in the field. The ARNI-Pro models were set up (1) along eight urbanization gradients to test the system's ability to detect community changes, and (2) in a variety of natural habitats across Germany to capture as many species as possible, ranging from raised bogs in the north to alpine habitats in the south. We also determine technical limits at extreme locations such as forest canopies and tropical environments and shortly assess the project's risks and exploitation perspectives. The ARNI-CS models further support the recording of the

community composition of nocturnal insects across various habitats in a citizen science context. The images and data generated by the ARNIs are uploaded to a scalable data management platform (LAUP = LEPMON Annotation and Upload Portal). LAUP processes the images and uses AI to enable large-scale object detection and species identification. As accurate AI models require extensive species-labelled training data, large numbers of manually identified images are needed. To obtain these identifications, we involve both taxonomic experts and citizen scientists. We aim to build international collaborations and share knowledge between countries, extending moth monitoring beyond Germany to strengthen LEPMON as a long-term biodiversity monitoring network.

Keywords

insect monitoring, data management, data integration, nocturnal insects, standardised sampling, community science

Introduction

Why monitoring of nocturnal insects?

Insects are by far the most species-rich group of animals and are of great ecological and economic importance (Takiya and dos Santos 2016). Many studies worldwide show an alarming downward trend in insect populations (Felgentreff et al. 2023, Hallmann et al. 2019, van Klink et al. 2020), which has led to an increased interest in their monitoring. However, existing insect monitoring programs are spatially, temporally and taxonomically limited, underlining the need for reliable, quantitative data on long-term trends of insect populations. Automated approaches could fill this gap, but the methods are currently not sufficiently developed to conduct detailed and comprehensive monitoring of insects in Central Europe. Lepidoptera (moths and butterflies), one of the most species-rich insect groups, are particularly well suited for the development of such approaches. Many species serve as valuable ecological indicators because of their dependence on specific host plants (Beck et al. 2016, Conrad et al. 2006), and their attractive appearance makes them popular with the public (van Tongeren et al. 2023). Moreover, because their wing surface area is large relative to their body size, many Lepidoptera can be reliably identified from photographs, making them promising candidates for automated image-based monitoring. In Germany, there are 3,682 species of Lepidoptera (Gaedike et al. 2017), including 166 species of diurnal butterflies and burnet moths, and approximately 1,160 species of macromoths (Steiner et al. 2014, Settele et al. 2025). Their body sizes range from 3 mm in the smallest microlepidopterans to 135 mm in the largest saturniid moth species (Segerer et al. 2011, STONIS et al. 2021), with larger moths being better studied.

Below, we present the LEPMON project (acronym derived from LEPidoptera MONitoring). The proposal for the project was submitted to the Federal Ministry of Research, Technology, and Space (BMFTR) in April 2024 and approved following peer review. LEPMON runs from December 2024 to November 2027. The goal of the project is to develop a powerful, stable and scalable system within three years that allows efficient monitoring of nocturnal insects in Central Europe, with a focus on macromoths.

Towards automated camera systems for insect monitoring

Traditionally, light trapping is the primary collection method for nocturnal Lepidoptera. In principle, this method attracts many flying nocturnal insects (Fabian et al. 2024). To survey the fauna of moths and other insects, they have traditionally been captured and identified individually. The required manual methods are time-consuming, which is why other methods have gained tractionin recent years, including DNA barcoding and metabarcoding (Buchner et al. 2024).

Camera traps offer an important alternative, with the advantage that high resolution images can be produced and no insects need to be captured or killed, and that the necessary human labour is strongly reduced compared to traditional methods (Fischer and Larson 2019, Holzhauer et al. 2026). Automated insect cameras can potentially operate continuously over long periods of time and throughout the night, offering significant advantages over conventional methods. When camera traps are used, a scalable, automated approach to species identification using artificial intelligence (AI) for the analysis of images is essential (details below). However, toward a reliable methodology, many technical challenges still need to be addressed (Montgomery et al. 2021).

In a broader context, the use of automated cameras has already become the standard method in ecological research focusing primarily on large wildlife (Burton et al. 2015, Delisle et al. 2021). Although the recording and monitoring of insects remains challenging due to their small size, diversity and difficulty of identification, efforts using automated camera systems have increased (Collett and Fisher 2017, Hogeweg et al. 2019, Preti et al. 2020) and interest in developing appropriate camera systems has risen (August et al. 2025, Bjerge et al. 2021, van Klink et al. 2022). In principle, standardized insect monitoring appears possible, but many problems have only been addressed recently, such as insufficient image resolution or a lack of training data for AI-based object detection and species determination. This has led to only a small number of species being evaluated systematically whereas most species could not be identified (Bjerge et al. 2021). However, Holzhauer et al. (2026) showed that high resolution automated cameras capture very similar communities as traditional methods resulting in detailed species lists of macromoths.

In the following, we do not refer to our devices as “camera traps”, as this term might be associated with the idea that insects are actually trapped or even killed. Instead, we call them ARNIs (Automated Recorders for Nocturnal Insects), which are designed to provide high resolution images, operate continuously with minimal disturbance of the insects, and require only low maintenance.

Data management

The massive amount of data from camera-based observations requires reliable and scalable data-management infrastructure that not only stores observations, but also records sampling metadata, supports scalable image processing, object detection, tracking and classification, and makes the resulting data available for subsequent analyses (Roy et al. 2024). Several platforms and research infrastructures already support the upload and AI-assisted processing of camera-trap images, including ARISE (Kloeke et al. 2025), the Antenna Data Platform (InsectAI 2026), Mothbox and Mothbot (Szczygieł et al. 2026).

With LEPMON, we extend this concept by focusing on the provenance and validation of the identified objects. Rather than treating human participation primarily as a human-in-the-loop mechanism for correcting AI classifications, we create an online virtual collection and identification community around automated monitoring where taxonomic experts and citizen scientists collaboratively annotate, review, and validate the observations of the moths. Additionally, we preserve the sampling effort: regularly acquired camera images are retained as part of the monitoring record regardless of whether target organisms are detected. This enables the analyses of species absence and detection probability that cannot be derived reliably from occurrence records alone.

The LEPMON data infrastructure provides an open research environment for transforming automated insect-camera observations into validated biodiversity data through integrated AI-based classification, citizen science annotation and expert taxonomic validation. The platform preserves the complete provenance of each identification and enables users to discover, filter and create reproducible species occurrence datasets from our distributed ARNI networks.

These functions are implemented in the LEPMON Annotation and Upload Portal (LAUP), which forms the central data-management component of the LEPMON infrastructure. In addition to its collaborative annotation and validation workflows, LAUP addresses operational requirements of large-scale camera monitoring, including secure image transmission, efficient storage, scalable processing, and high-performance visualization of large image collections and derived results.

LAUP is available at: https://lepmon.de/annot8/

Artificial intelligence for species recognition

The large amounts of photos generated by cameras from many sites over longer periods of time cannot be processed manually as the effort would be too great – but they can effectively be processed by AI models. Accurately identifying insects with AI at a low taxonomic level (ideally species) is needed to improve our large-scale understanding of moth population dynamics over long periods of time. The first studies aimed to automate moth classification made use of manually defined characteristics of moths, such as colour and shape, to distinguish species (Mayo and Watson 2007, Loy and Eklundh 2006).

With the increased popularity of using AI, image-based AI models would learn these distinguishable properties themselves. Even though technology improved and many studies attempted to build reliable moth classifiers (Chang et al. 2017, Hansen et al. 2019 , Ong and Hamid 2022, Wägele et al. 2022, Xia et al. 2018), models were often still limited, as they had only a small amount of training data available and only a limited number of species could be accurately predicted.

The AMMOD project (Automated Multisensor Stations for Monitoring of BioDiversity; Wägele et al. 2022) built on this research by delivering a model capable of distinguishing 200 moth species, which LEPMON will further extend. Images delivered from ARNIs stand out because of their high image resolution, which is particularly relevant for moth identification given the small visual differences between the many species.

Citizen Science

With advances in technology, the importance and utilisation of citizen science – the involvement of volunteers in scientific research – and gamification in ecological research is increasing (Pocock et al. 2017). Mass-recruitment of volunteers enables the collection of large amounts of data across large spatial scales in a relatively short time (Sheard et al. 2021).

To date, most citizen science projects have focused on common and recognisable species that are observed opportunistically in convenient, accessible areas (Ward 2014). Data is typically collected using mobile phones in an ad hoc manner and uploaded to online platforms such as observation.org and iNaturalist.org. Projects using more advanced technologies and rigorous sampling designs remain relatively rare (Sheard et al. 2024). However, to study biodiversity change, systematic and continuous long-term collection of data at fixed locations is essential. Standardized technologies can continuously detect and record rare and elusive species that are easily overlooked by humans, thereby allowing more accurate estimates of biodiversity.

LEPMON involves volunteers in recording biodiversity by enlisting them in operating ARNIs and systematically collecting images to facilitate long-term nationwide biodiversity monitoring. Crucially, LEPMON also engages and recruits taxonomic experts from local nature conservation associations to help annotate images and train the AI. In doing so, we explore optimal methods for volunteer engagement through the implementation of gamification elements within the LEPMON Annotation and Upload Portal.

Application of ARNIs in urban gradients and in habitats

To test the utility of the developed system for ecological research and monitoring, LEPMON investigates how urbanization affects the diversity of nocturnal insects across Germany. Urbanization is a known cause of biodiversity loss among insects (Fenoglio et al. 2020, Wagner 2020, van Klink et al. 2020). As such, we expect to find a significant decline in species diversity with increasing urbanization. Up to five ARNIs are set up in each of eight cities in Germany, along gradients of increasing percentages of sealed surface.

Our approach has several advantages, as we do not rely on labor-intensive trapping and morphological identification of individual insects. LEPMON is far less limited regarding the number of sites and particularly the number of nights when data is collected. If 34 ARNIs collect data along the urbanization gradients, this amounts to 34 * approximately 180 days per year, assuming the devices operate from April through September. This is equivalent to more than 6,000 collecting nights per year—a figure that even ambitious conventional projects could never achieve. A practical advantage of working with urban gradients as a model is that it may be easier to find volunteers who can set up the devices in their yards compared to rural regions. In addition, it is easier to arrange power supply in populated areas with access to grid electricity than in the open countryside.

In addition to urban gradient sites, we also set up ARNIs in a wide variety of habitats across Germany. This allows us to collect training data from as many species as possible (especially those not found in urban habitats).

LEPMON deliverables:

- We provide the fundamentals for long-term, standardized monitoring of nocturnal insects in Central Europe and connect engineering with computer and biodiversity science.
- We are developing two types of ARNIs: the Pro version for professional users and the more affordable citizen science (CS) version. Both can reliably capture high-quality standardized images of moth communities, which can be analysed at species level. This includes the development of hardware and software and encompasses commercial providers.
- We investigate the performance of ARNIs under challenging environmental conditions such as forest canopies and the tropics.
- ARNIs are being installed in urban areas and in a variety of different habitats ranging from raised bogs in the north to alpine habitats in the south in collaboration with local stakeholders, and their functionality is being broadly tested in practice.
- ARNI data is uploaded onto a newly developed, scalable data management platform (LAUP). It stores image data and implements AI to enable object recognition and mass species identification.

- We develop methods for online annotation and identification, and new AI models for species recognition as well as diversity estimates of macromoths in Central Europe. We integrate specialist knowledge from biodiversity research and ecology into AI models.
- With the click of a button, species lists of all identified macromoths should be available, along with estimates on the reliability of the identifications. It should be possible to filter the lists by taxon and region.
- We conduct a citizen science project to develop an optimal approach for a national monitoring system. This includes testing recruitment strategies, volunteer motivation, the ideal target group, device deployment, data collection and annotation methods.
- Using species-level data of macromoths generated from ARNIs and stored on LAUP, we investigate biodiversity loss along urban gradients in eight German cities. This includes the analysis of the impact on various environmental variables such as soil sealing and vegetation richness on the diversity of moths and other insects.

LEPMON Consortium

The project consortium brings together Friedrich Schiller University Jena (FSU) with its two departments of Biology (FSU-Bio) and Computer Science (FSU-Inf), Philipps University Marburg (UMR), the Leibniz Institute for the Analysis of Biodiversity Change (LIB), and the German Centre for Integrative Biodiversity Research, an interdisciplinary research unit of the Martin-Luther-University Halle-Wittenberg (MLU-iDiv, Fig. 1). LEPMON covers the entire process from product development to large scale deployment for ecological testing. FSU-Bio leads the project, develops ARNIs, manages ARNI-Pros, and coordinates the expert work. LIB is responsible for database management, data transfer, interfaces to the database, and the annotation and identification system. FSU-Inf uses the resulting image data with annotations and develops the necessary AI models for automated species identification. UMR involves citizen scientists in the project and maintains ARNI-CS. MLU-iDiv is responsible for the statistical evaluation and analysis of data as well as the identification/annotation of other insects. Regular meetings within the project keep all partners up to date. For the urban gradients, we collaborate with local partners across Germany (Fig. 1, grey circles). For the technical tests of ARNIs, FSU-Bio collaborates with the Bavarian Forest National Park Administration and the Fundación Jocotoco (Quito, Ecuador). Environmental authorities and planning offices are interested in operating the stations to carry out environmental impact assessments or obtain data from protected areas.

ARNIs

ARNIs are designed to reliably and autonomously attract insects at night and capture images that can be used to identify the vast majority of larger Lepidopterans at species level. A LED UV lamp (3 W) effectively attracts insects (Brehm 2017, Fabian et al. 2024).

Many of these eventually land on a screen made of polyethylene foam where they sit and rest. The screen is illuminated by a white LED for two seconds every two minutes during the night when photographs are taken. This helps save energy and allows the system to operate as inconspicuously as possible. The camera and the control electronics are positioned opposite the screen and housed in a protective enclosure.

We have developed two versions of ARNIs: ARNI-Pro (Fig. 2 A-J) and ARNI-CS (Fig. 2 K-L), which collect images and metadata that are technically comparable to each other. Both ARNI versions share essential components, i.e. the same UV lamp and most of the electronic components, including a Raspberry Pi 4B computer and a custom-made printed circuit board in combination with corresponding firmware written in Python. Both versions capture images with an effective resolution of 16 pixels/mm that allow the reliable identification of all macromoths and many of the larger micromoths (see Figs 3, 4 for examples). ARNI Pros are operating with an industrial camera and professional lens (sensor size: 3672 * 5496 px) and a screen size of 240 mm * 360 mm. ARNI-CS uses a smaller and cheaper Raspberry camera (sensor size: 2592 * 4608 px). To compensate for lower sensor size, the size of the screen of ARNI-CS is reduced (265 mm * 150 mm), as well as the distance between screen and camera, resulting in a much more compact design (Fig. 2). The effective resolution of both ARNI variants is higher compared to other monitoring devices, which use a smaller sensor size, such as the Lepisense (UKCEH, United Kingdom), Diopsis (Faunabit, Netherlands) or Mothbox (Szczygieł et al., 2026) systems. ARNIs will be described in more detail in a separate paper. ARNIs are not restricted by patent rights, and the required components are readily available from different companies. ARNI-Pro is commercially available via the manufacturer (K2W Lights, Jena, Germany) and ARNI-CS will be available in the future.

The central type of data collected by ARNIs is the image of the insects. ARNIs capture images in jpg format in high quality (95% compression). Data are stored locally on a USB flash drive (recommended size: ≥ 256 GB) along with log files with standardized and computer readable content. A single jpg image has a size of 3-11 MB. Each file is assigned a unique ID (LEPMON-Code) that can be used to link the image, all derivatives, and all data and metadata. The unique LEPMON-Code consists of the serial number of the ARNI, an abbreviation of the location with province and city, and the timestamp. An example image of ARNI-Pro encoded ‘Lepmon#SN010030_TH_J_2025-07-03_T_0122’ can be seen in Fig. 3. The image was taken by ARNI 010030 in Jena, Thuringia on July 3, 2025, at 01:22 a.m.

A map shows all ARNIs installed by 18.08.2026 (Fig. 5). Up to five ARNI-Pros are operating along urban gradients in the cities of Bremen, Bonn, Marburg Jena, Leipzig, Ludwigshafen, Regensburg and Freiburg, with each gradient from the city center to a forested area on the outskirts. Sites were selected based on the imperviousness of the area in a 100 m radius surrounding the ARNIs (Copernicus and Land Monitoring Service 2021). In addition, project partners set up 33 ARNI-Pros in a variety of habitats targeting more specialist, rare and locally occurring species. We have integrated some ARNIs into existing monitoring programs to establish long-term relations, such as the Leipzig Canopy Crane in Leipzig. Externally funded devices further expand coverage, e.g. by the

National Parks Hamburgisches Wattenmeer and Harz. ARNIs should be operated for six months per year between early April and the end of September. This ensures that most moth species can be monitored throughout a season, that the power supply for solar-powered systems is guaranteed, and that the equipment is not damaged by harsh winter conditions. 37 ARNI-CS supplement the network distributed across a variety of habitats and more are being deployed by citizen scientists. They collect further training data on rare and locally distributed species and will be used to investigate differences in moth communities across broad habitat categories. Tests for the reliability and technical limitations of the system include the setup of ARNI-Pros in forest canopy (Bavarian Forest National Park, Germany) as well as hot and humid climatic conditions in the tropics (lowland rainforest in NW Ecuador). A further test of the comparability of data generated from the ARNI-Pro and the ARNI-CS is being run at five fruit orchard sites around Marburg.

Data management

The LEPMON data pipeline connects data acquisition by the ARNIs with centralized storage, AI-based image processing, collaborative identification, validation, analysis, and publication. Images and associated log files are initially stored locally on the ARNIs and transferred at regular intervals to the LEPMON Annotation and Upload Portal (LAUP) to which users need to register (Fig. 6). The productive version of LAUP is available at: https://lepmon.de/annot8. Fig. 7

LAUP provides research data management, image presentation, AI processing, collaborative annotation, and access to derived monitoring data within a common infrastructure. The LAUP portal's implementation stack is based on the Python-based Django web framework (Django 2026) as the backend, using the relational database MariaDB (MariaDB 2026) for data storage. The web interface is implemented using the Pylons/Pyramid web framework (Pyramid 2026). Results are delivered via Elasticsearch indexes (Elastic 2026). The backend and frontend communicate with each other via defined interfaces (API). LAUP integrates data originating from ARNIs with AI-generated detections and identifications, annotations contributed by citizen scientists and taxonomic experts, and results derived from downstream analyses (Fig. 6)

During upload, images are registered using unique identifiers that connect the image files to their sampling metadata and subsequent processing results. Metadata for each image, such as recording time, geographic coordinates, humidity, and temperature are extracted automatically from the log files. Images then enter an automated processing workflow, that detects empty images, corrects image quality and use specialized AI models to localize objects suggest classifications of individual insects (see next section). Detections of individuals that appear in consecutive images are grouped into tracks to avoid redundant annotation and repeated counting of the same individual. Importantly, LAUP treats the complete sequence of images as a record of the sampling process rather than retaining only images containing detected insects. Images without detections therefore remain associated with the corresponding sampling events. Together with information on camera location, recording time, and environmental conditions, these records document sampling effort and enable subsequent analyses to distinguish between positive observations and periods in which no target organisms were detected.

Rather than storing only the final species determination, the system maintains the relationships between the original image, the localized object, AI-generated identification proposals, subsequent human determinations, and expert validation. In this way, each observed insect becomes part of a provenance-aware virtual collection. The history and origin of a taxonomic determination can therefore be reconstructed and, where necessary, revised without losing earlier identification information.

LAUP additionally provides user management, search and filtering facilities, image and metadata visualization, data download, and interfaces for generating species lists. These functions allow users to select observations according to spatial, temporal, taxonomic, environmental, or other criteria and to derive subsets for subsequent biodiversity analyses. So far, we have collected a total of 2,315,601 images by 18.08.2026; this corresponds to around 11 TB of data stored. In these images, the AI localized 3,865,081 objects (moths and non-moths, e.g., spiders, wasps, beetles).

LAUP also manages the distributed network of ARNIs. For each device, information such as its location, model, serial number, deployment, and operational status is recorded. Future integration of technologies such as LoRaWAN could provide additional status information from cameras deployed at sites with limited network connectivity.

LAUP provides dedicated interfaces to facilitate manual human annotation and correction of AI localization results (see section *Localization, identification and taxonomic annotation*). Trait measurements can also be done for further enrichment of the Implementation of gamification methods is planned to increase user motivation for training and image processing tasks. The gamification aspects are further linked to user accounts and enable the gain of knowledge on species. Also, the role of taxon experts is assigned, who are essential for the success of the LEPMON project; they validate annotations made by citizen science users and AI.

Metadata and identification results are available to all users. Species lists can be downloaded via the web interface. A dedicated data catalog provides an interactive and integrative overview that promotes the development of new hypotheses and supports LEPMON in answering its research questions.

All data sets produced are securely stored and made accessible according to FAIR criteria for good data management, using the structures developed and defined by the German Federation for Biological Data (Grobe et al. 2019, Team GFBio 2018). Furthermore, data management is in accordance with the Deutsche Forschungsgemeinschaft (DFG) guidelines for handling research data in biodiversity research and the DFG guidelines for ensuring good scientific practice. The LEPMON consortium develops a formal policy for data release and to regulate the handling of monitoring data, including criteria for citation, reuse, transfer, and exchange of data within the project, as well as embargo periods for data release in accordance with the guidelines set by the DFG.

Validated occurrence data are intended for publication through national and international biodiversity infrastructures, including the LAND portal of NFDI4Biodiversity and GBIF. The validated occurrence data are intended for publication through national and international biodiversity infrastructures, including the LAND portal of NFDI4Biodiversity and GBIF. The data are provided in the Darwin Core Data Package Darwin Core Maintenance Group (2026) and Bubnicki et al. (2023) formats, which ensures interoperability with data from other monitoring projects. Data are accompanied by rich metadata and appropriate open licenses. Long-term preservation on LIB infrastructure ensures that monitoring results remain available beyond the duration of the project. The LAUP source code is published as open source on the LIB GitLab instance (https://gitlab.leibniz-lib.de/lepmon/laup).

Artificial intelligence examples and goals

We develop specific AI methods for species recognition using collected images from the ARNIs and additional data sources. We aim for robust models that enable automated image analysis and species identification of Lepidopterans and other insects to species level. The performance of the trained AI models should reach a level that enables robust species detection and identification so that reliable statements about changes in biodiversity at various locations in Germany and over different observation periods can be derived in the subsequent data analysis. Projects with comparable, yet distinguishable automated cameras (LepiSense: https://nerc-ceh.github.io/lepisense-website and DIOPSIS: (https://diopsis.eu/en/) also have developed AI systems for insect recognition. However, the resolution of the images captured is lower compared to those taken by ARNIs, which limits the species-level identification for smaller moths (such as shown in Fig. 4 I-P), leading to different monitoring options.

With many of the 3,682 known Lepidoptera species in Germany represented by only a few training examples, the task is challenging due to strong class imbalances. The training data for the AI models consist of annotated sample images of insects, which depend on manual identification by experts. Validated images can be found on online platforms such as gbif.org and lepiforum.org, providing large and diverse sources of training data. The resulting class imbalance makes high-quality, taxonomically validated training data especially important. LEPMON therefore combines existing image resources with images acquired under the standardized conditions of the ARNIs. In LAUP, model predictions are stored as identification proposals associated with a particular image object and model execution rather than being treated automatically as final taxonomic determinations. Depending on confidence, taxonomic group, and intended use of the data, these proposals can subsequently be accepted, revised, or replaced through citizen science annotation and expert validation. This allows the generation of larger annotated training data sets, which are essential for AI training and further improvement of the models.

AI has shown its potential of species identification for automated biodiversity monitoring for a large number of moth species (Wägele et al. 2022). A demonstration system can be tested online (https://moths.inf-cv.uni-jena.de/, Fig. 8).

Our first classification model applied to images recorded with an early ARNI prototype in 2022 achieved an accuracy of 92% when classifying 80 moth species (n = 2356 images). We also reached 93% accuracy on the EU-Moths benchmark dataset by developing a model that already had some existing ecological knowledge and additionally could put extra importance to the most informative body parts (Korsch et al. 2023). YOLOv9-E, our best performing model for locating moths within images, achieved a 97.2% AP50 on the AMI-Trap dataset (Yu et al. 2025), where AP50 is a standard metric for localization and detection accuracy.

Beyond image appearance alone, we test the benefits of including additional information, including morphological traits such as size, colour, shape and symmetry, as well as taxonomic relationships between species, genera, families and orders into our models. This additional information could support both localization and species identification, two directions that already explored by initial research within the LEPMON consortium (Korsch et al. 2022, Korsch et al. 2023a, Korsch et al. 2023b). Traits, such as data on size and colour can be extracted automatically by the LEPY pipeline from individually photographed spread specimens (Correa-Carmona et al. 2026) but can also be entered by the users of the LAUP portal in a standardized way (Fig. 9). Building on this approach, we are currently developing a method to extend these measurements to images taken in the wild, using pixel-to-millimetre calibration against a large wingspan database. We also test moth contour analysis, including shape and symmetry, as well as visual explanation map methods that show the regions of the moth contributing most to the prediction. Hierarchical models that use relationships between taxonomic levels have already been explored within AMMOD and LEPMON (Brust et al. 2021, Brust and Denzler 2020, Barz and Denzler 2019), and further developing these approaches is high on our list of priorities.

In addition to Lepidoptera, we also plan to consider other insect orders that are captured by ARNIs to be integrated and automatically identified by AI models to allow full use of the data collected by ARNIs and provide a more complete picture of ecological communities.

An exciting feature still under development is to translate our model species predictions into meaningful ecological information. Instead of only identifying individual moths, we aim to show where species occur, how their numbers and diversity change over time, and how biodiversity differs between regions. These outputs will make the information generated by the ARNIs easier to interpret and use for biodiversity monitoring and conservation, and we look forward to reporting more on this work as it develops.

Localization, identification and taxonomic annotation

The processing of an insect image involves conceptually distinct steps that are represented separately within LAUP. We use localization to describe the detection of an individual insect and the determination of its position within an image. We use identification or taxonomic annotation for the assignment of a taxon to that localized object. Finally, validation refers to the assessment of an identification by a suitably qualified taxonomic expert. Localization is represented by a bounding box defining the position of an insect within an image. Bounding boxes are generated automatically by our AI model in LAUP or contributed and corrected manually by Citizen Scientists. Because automated cameras acquire sequences of images, localized objects are also be associated across consecutive images to form tracks.

Localization does not require detailed taxonomic knowledge and can therefore be performed by a broad group of participants. Taxonomic identification requires a different workflow. For each localized object, The AI models in LAUP propose one or several candidate taxa. Human participants can accept a proposal, select an alternative taxon, identify the object at a broader taxonomic level, or leave it unidentified when the available evidence is insufficient. The system consequently does not force every observation to receive a species-level determination (Fig. 10).

A central feature of this workflow is that different determinations are not collapsed immediately into a single species label. Instead, AI predictions and human annotations remain attributable to their respective sources. Taxonomic experts can subsequently review these determinations and provide validated identifications. This makes it possible to distinguish, for example, an unreviewed AI prediction from a citizen-science identification or an expert-validated record when data are selected for analysis. Thus, we record annotator expertise and validation history rather than treating a human annotation as ground truth.

The resulting provenance information is particularly important because taxonomic identifications may change. By retaining the relationship between the image object and its sequence of identifications, LAUP allows such changes to be documented without losing the history of previous interpretations.

Citizen science

We develop and test citizen science and gamification methods for monitoring nocturnal insects. This campaign includes the application of the ARNI-CS. The focus is on motivations of taxon experts and volunteers without a scientific background or knowledge of moths for participation. The amount of data collected through citizen science can become a problem, as the number of volunteers usually far exceeds the number of experts. For the ARNI to be interesting to volunteers, it must be able to deliver results (e.g., species lists) quickly. This requires advanced AI trained on thousands of annotated images. Hence, the success of LEPMON directly relies on the contribution of volunteers, and enthusiast in identifying insects. The automatic search for similar reference images by the AI model is a central component of the playful design of the annotation process. Citizen science in LEPMON is integrated directly into the scientific workflow rather than being treated solely as a mechanism for correcting erroneous AI predictions. The objective is to establish a community around the virtual insect collection generated by automated monitoring, in which participants with different levels of expertise contribute complementary information. Tasks can therefore be matched to participants' knowledge. Volunteers without specialist taxonomic experience can contribute to insect localization, review images, and perform identification tasks for which sufficient guidance is available. More experienced participants can contribute taxonomic determinations, while designated taxon experts validate difficult or scientifically critical records.

Participants in the annotation project can also discuss the images they have annotated and compare their annotations. Additionally, they can improve their identification skills through a training program in Quizlet (http://www.quizlet.com). Teaching and training materials for species identification in the form of texts and illustrations further engage volunteers. We conduct annual surveys to gather important feedback from participants. All volunteers and practice partners will be invited to online meetings to provide information on the current state of development and to obtain feedback. Continuous communication takes place via online workshops and includes technical support for ARNI and LAUP.

The interaction among AI, citizen scientists, and taxonomic experts within LAUP consequently forms a collaborative identification process. Citizen scientists are not merely correcting an algorithm, and experts are not merely producing labels for machine-learning models. Instead, all three components contribute evidence to the identification history of an observation, while LAUP records their respective provenance and provides mechanisms for validation. This approach also creates a direct connection between participation and scientific output. Once observations have reached an appropriate level of validation, participants and researchers can use LAUP to explore the resulting monitoring information and obtain species lists and other derived data products. The virtual collection thus links the act of examining individual insects with larger questions concerning species occurrence, temporal change, spatial variation, and biodiversity trends.

While new technologies such as the LEPMON systems open many opportunities for citizen science and biodiversity monitoring, there are also concerns that the involvement of technology could exclude participants and reduce volunteers' connection to nature (Altrudi 2020, Sheard et al. 2024). Therefore, careful examination of the motivations for participating in citizen science, the benefits of gamification approaches, and the potential negative consequences of using technology in citizen science is necessary.

Evaluation

We test the large-scale application of ARNIs and its potential uses for ecological research and biodiversity monitoring. This includes the ability to produce scientifically usable data, which are based on AI-driven image processing, and reliable results as well as their large-scale application. If this is the case, the system can be used for studies to clarify cause-and-effect relationships such as environmental impact assessments, ecological research, and biodiversity monitoring.

We test on urban gradients as urbanisation is a known cause of insect diversity loss (Fenoglio et al. 2020), including insect decline (van Klink et al. 2020), and it is associated with habitat destruction, pollution, and disturbance. We therefore expect to find a negative correlation between the degree of urbanization (e.g., measured as the proportion of sealed surface area near the trapping sites) and moth diversity in the data collected with ARNI. We develop statistical tools to provide reliable abundance estimates of the species identified and analyse our data. This includes, e.g., avoiding double counting so that corrected abundance lists of species are available. Using this data, we will then statistically analyse the effects of urbanization and direct environmental factors at each location in the eight cities studied.

It is also important to understand the biases in the data collected for the future usefulness of a national or international citizen science project. It has been shown that traditional trapping with funnel traps is comparable with automated insect cameras (Holzhauer et al. 2026). We expand these comparisons and investigate the comparability between the ARNI-Pro and ARNI-CS, which are used on a broad scale by different user groups to ensure the reliability of collected data.

Outreach

A large-scale research project such as LEPMON also requires an outreach strategy tailored to different target groups. We organized a stakeholder workshop at the beginning of the project. The workshop allowed discussion of ideas and questions about important technical aspects as well as experience in biodiversity monitoring programs. LEPMON members regularly attended a variety of conferences to promote the project and gather volunteers and experts including the meetings of the Thüringer Entomologenverein, the Tagfaltermonitoring Deutschland, Westdeutscher Entomologentag, Münchner Entomologische Gesellschaft and the European Congress of Lepidopterology as well as meetings of the Forschungsinitiative zum Erhalt der Artenvielfalt (FEdA) and Research for sustainability (FONA). We have launched the bilingual website lepmon.de, which provides information on all aspects of the project, offers software updates, and links to LAUP. We participated in educational events, wrote various press releases, have been interviewed for the local news, and produced a video that is being shared more widely by FEdA.

Members of the LEPMON consortium are actively participating in the Europe wide COST action InsectAI (August et al. 2025). We are part of a network of developers of solutions for monitoring insects with different focus compared to LEPMON, such as Diopsis (Faunabit, Netherlands), Insect detect (Sittinger et al. 2024) and AMI trap in combination with the Antenna platform (Bjerge et al. 2021, InsectAI 2026). We have started to publish our findings in peer-review scientific journals (Holzhauer et al. 2026, this paper).

Economic prospects and service to society

Research must also address the question of whether this leads to economic and social benefits. LEPMON and its scientific institutions do not directly pursue commercial interests, but we collaborate with partners in the industry and further establish such relationships. We also cooperate with the Research Initiative for Biodiversity Conservation (FEdA) for the transfer of technology like AI developments to other fields of research.

LEPMON’s activities will result in long-term benefits through the contribution to the education of young scientists. The experience, findings, and results gathered can form the basis for further, third party-funded projects, either in the fields of biodiversity monitoring or ecological research.

All LEPMON algorithms, software, images, AI methods and data will be made available to science and society through open access publications or publication on GBIF. The data infrastructure, including databases and the LAUP data portal is accessible on GitLab. The infrastructure technology with connections to GBIF and specialist portals forms a product that can be easily transferred to similar monitoring projects.

Given the data we already have, we are confident that results from LEPMON have a great potential to better understand the decline in insect populations. Hopefully, this will have an impact on political decisions on environmental protection and Germany's sustainability goals, but also about international efforts, such as the UN Decade on Ecosystem Restoration and the international Sustainable Development Goals.

Risk assessment

As can be expected, there are some risks in the project: For example, different kinds of malfunctions can occur during ARNIs operation either on the hardware or the software side which are reported in the log files on the flash drive. The most common issues have occurred when initializing ARNIs camera module, sensors or accessing the flash drive. These problems get tested while a user maintains an ARNI, so an immediate fix is usually possible. Additionally, ARNI further solves reoccurring issues with a reboot.

There is also a risk of theft and/or vandalism of ARNIs. We have therefore given preference to installing ARNIs on private/fenced properties. In publicly accessible areas, the locations should be low traffic. We provide information boards and mandatory warning signs, as this has proven effective in many citizen science projects. As of August 2026, no ARNI was stolen, but one was damaged and two solar panels were stolen.

There are risks of server failure and the associated collapse of the entire system. The LIB participates in a security audit for servers and the Internet to quickly identify and address potential security risks. The server infrastructure is cloud-based; all applications are installed and put into production via continuous deployment from a Gitlab repository. In the event of a server failure, it is possible to switch to another server and restart the applications. The risk of a failure in LAUP lasting more than one day is low.

It has proven more difficult than expected to find enough volunteers willing to set up an ARNI in the cities. For this reason, Würzburg was replaced by Regensburg, and we were unable to fill all 40 planned locations—only 34.

Some moth species might be rarely or never recorded by ARNIs. Similarly, there may be too few images of other insects to expand the AI models to include such species. ARNIs are therefore operated in a large variety of habitats, and we will obtain further training data from images of collection material from museums.

Insufficient accuracy of AI models for data evaluation is a potential risk for the monitoring database and analysis. Our AI models already enable identification accuracies of over 90%. The integration of expert and application knowledge into the AI models is carefully developed and offers great potential for further improvements. Recognition performance also improves with training data collected in the project. Unexpectedly high error rates, especially for rarely observed species, can be countered by manually verified data. Error rates and uncertainties in the determinations must be appropriately modelled and considered in the data evaluation.

LEPMONs long-term legacy depends on successful developments achieved during the project and convincing performance in all aspects as well on securing funding to maintain the necessary infrastructure and technical support.

Conclusion

LEPMON drives the development of large-scale, long-term standardized monitoring of nocturnal insects. The system consists of high-resolution automated cameras, a scalable monitoring database with reliable data management and automated processing of the recorded image data by AI models for species identification. It reveals spatial dynamics and enables the collection of data over long periods of time — data that cannot be captured in this form using previous methods. At the same time, data in the form of images is highly transparent and allows for validation and, if necessary, correction at any time, which sets it apart from methods such as DNA metabarcoding. The experience, insights, and results gathered in this project can open broad perspectives for biodiversity monitoring in applications such as pest control and in many aspects of ecological research.

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Conflicts of interest

The authors have declared that no competing interests exist.

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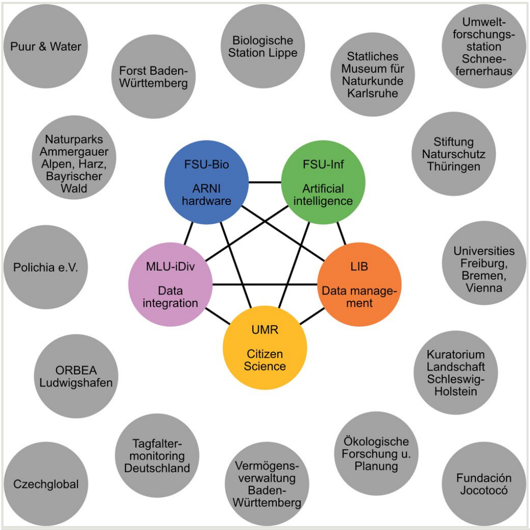

Figure 1.

Project partners (inner pentagon) and practical partners (grey circles) of LEPMON; Friedrich-Schiller-University Jena (FSU), Leibniz-Institut zur Analyse des Biodiversitätswandels (LIB), Philipps-University Marburg (UMR) and German Centre for Integrative Biodiversity Research - Martin-Luther-Universität Halle-Wittenberg (MLU-iDiv).

Figure 2.

Automated recorders for nocturnal Insects (ARNIs) installed in the field in both variants (ARNI-Pro, A-J) and the smaller ARNI-CS (K-L). ARNIs are installed along urbanization gradients from forest to highly sealed environments (A-C, Jena), and in various habitats across Germany (all other images). They can be powered by solar panels (E-G, I). Insects are attracted at night by a UV insect lamp and are photographed on a white screen in intervals of two minutes. The size of the screen is adjusted to sensor size to allow an effective resolution of 16 px/mm in both variants. See Fig. 5 for a map where ARNIs are located.

Figure 3.

Sample image from an ARNI-Pro installed in Jena, Germany, captured at 01:22 a.m. on 03.07.2026. Screen size: 24 * 36 cm, Scalebar 10 cm.

Figure 4.

Examples of moth photos taken by ARNIs (Pro model) with a resolution of 16 px/mm shown at different scales; each scale represents 10 mm. A) *Saturnia pavonia*, B) *Deilephila porcellus*, C) *Sphinx pinastri*, D) *Catocala promissa*, E) *Colocasia coryli* (left) *and Diacrisia sannio* (right), F) *Pachetra sagittigera*, G) *Calliteara pudibunda*, H) *Acronicta psi/tridens* complex, I) *Epirrhoe alternata*, J) Crambinae (top) and *Drepana falcataria* (bottom), K) *Idaea aversata* (centre), *Cnephasia* sp. (top), and unknown species (bottom), L) *Mythimna pallens*, M) *Pyrausta despicata*, N) *Rivula sericealis*, O) *Scoparia* sp., P) *Nola confusalis*.

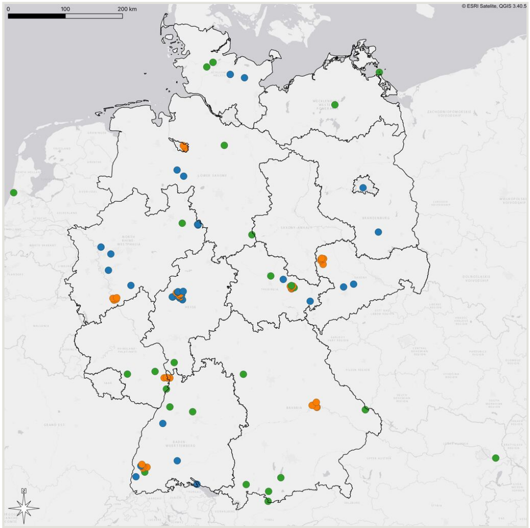

Figure 5.

102 Deployed ARNI devices by 18.08.2026 across Germany (map with borders of the federal states). Note that two ARNIs are also located in the Netherlands and Austria. Circles represent locations of ARNI-Pro in urban gradients (orange, 34 ARNIs) and in habitats (green, 33 ARNIs) as well as ARNI-CS (blue, 37 ARNIs). More ARNIs will be installed in 2027.

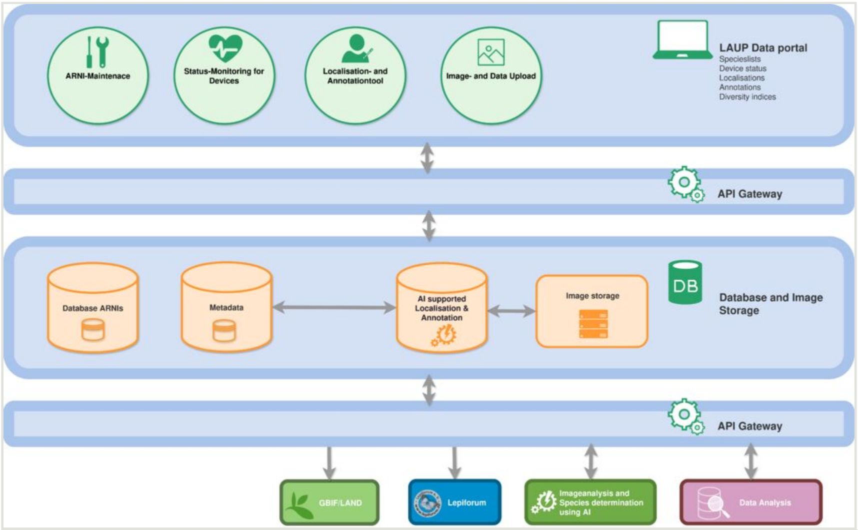

Figure 6.

Data flow within LEPMON between the individual nodes of the information infrastructure. ARNI and recording metadata, image uploads, AI processing, collaborative annotation, validation, and analytical outputs are connected through the central application, database, and image-storage components. External applications and publication services can interact with the infrastructure through APIs. The infrastructure enables central management, provision, and backup of all data and results generated in LEPMON. Note: the publication of research grade data to GBIF and other platforms is work in progress.

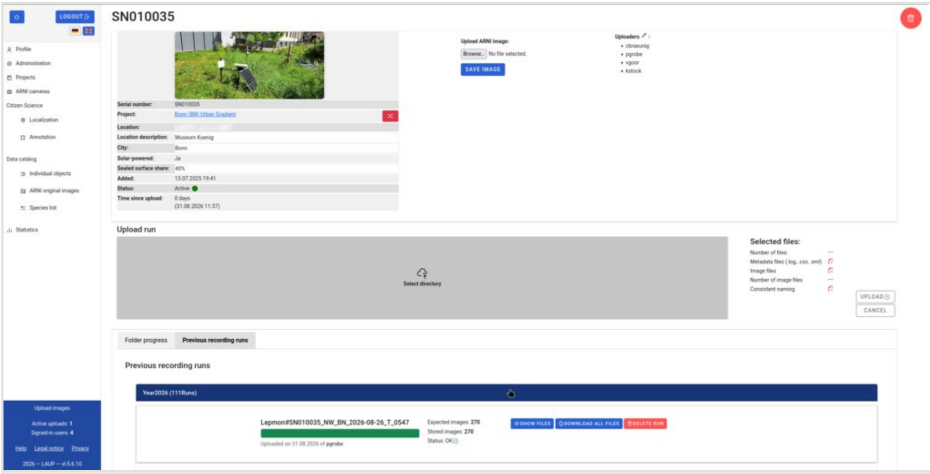

Figure 7.

Screenshot of the LAUP Portal Version 5.6.10, showing the upload screen for an ARNI device with serial number SN010035, as well as information on the collection site and activity. A list of previous uploads can be used to verify the completeness and quality of images that have already been uploaded. One or more users can be assigned extended administrative rights as “uploaders” for the ARNI device, such as the right to delete uploads. The portal provides interfaces for uploading, managing, searching, annotating, validating, and downloading data generated within the LEPMON project.

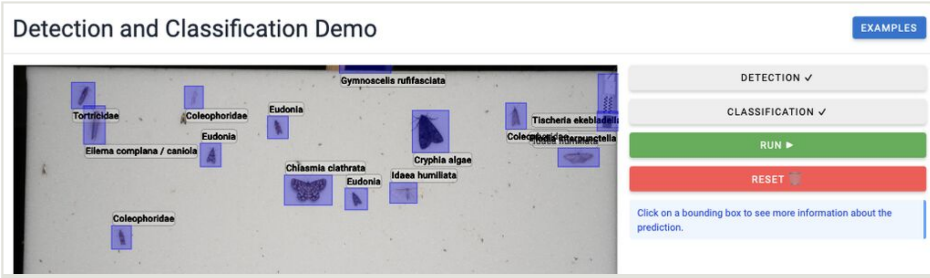

Figure 8.

Screenshot of the demonstration website, showing detection and localization of individual moths with rectangular bounding boxes and up to species-level identification. Available at https://moths.inf-cv.uni-jena.de/.

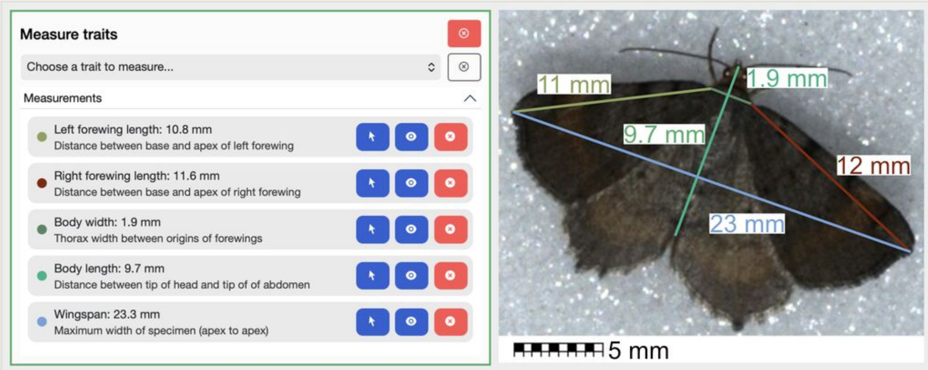

Figure 9.

Example of additional information derived from moth images. Screenshot from the annotation feature for traits in LAUP (moth: *Macaria liturata*).

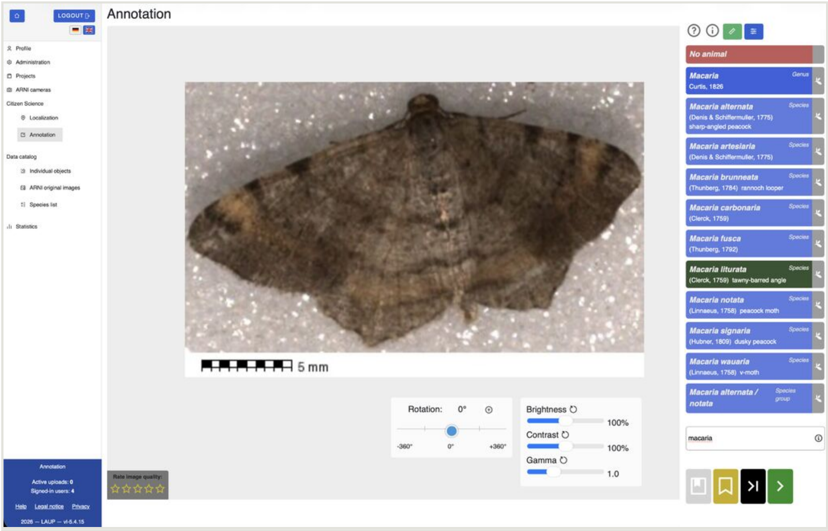

Figure 10.

Screenshot of the LAUP Portal Version 5.4.14. with annotation options for a localized, individual moth (*Macaria liturata*). Users can search and select the name of a specimen on the right-hand side (blue boxes) and save (green arrow). Uncertain ones can be skipped (black arrow). Tools for display options are found below the specimen photo.