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E-Mail: nwv@landesmuseum.ktn.gv.at
Website: www.naturwissenschaft-ktn.at

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CONTENT

Trying to find common ground: On the fourth issue of Carinthia Nature Tech

Susanne Aigner, Daniel Dalton, Michael Jungmeier

Time passes quickly, and the fourth issue of *Carinthia Nature Tech* is already in your hands. We are pleased that this young journal continues to develop so robustly. The routines in editing, peer review, design, and publication are beginning to settle in. We are grateful for the important contributions of our editorial board, which were especially evident and tangible at the last meeting on April 8th (Figure 1). The journal is gaining an international readership, and we are delighted by the growing interest in Carinthia's contributions to natural resource management.

Fig. 1

Figure 1: Editorial Board. We appreciate the support of the high-caliber board, shown here at a hybrid meeting on April 8, 2026 at Carinthia University of Applied Sciences; from left to right: Franz Hölzl, Gernot Paulus, Peter Granig, Wilfried Elmenreich, Ilja Svetnik, Michael Jungmeier, Susanne Aigner, Lilia Schmalzl, and Daniel Dalton; on screen: Christian Komposch, Tamara Schenekar, and Daniel Mengistu. Photo: Lily van der Donk.

Abbildung 1: *Redaktionsbeirat. Wir freuen uns über die Unterstützung des hochkarätigen Beirates, hier bei einem hybriden Treffen am 8. April 2026 an der Hochschule Kärnten; von links nach rechts: Franz Hölzl, Gernot Paulus, Peter Granig, Wilfried Elmenreich, Ilja Svetnik, Michael Jungmeier, Susanne Aigner, Lilia Schmalzl und Daniel Dalton; am Bildschirm sichtbar: Christian Komposch, Tamara Schenekar und Daniel Mengistu. Foto: Lily van der Donk.*

Thanks to funding by the Austrian Science Fund, FWF, an online editorial system has been set up and is now in operation. This enables an online workflow from submission and peer review to production and publication. The funding has enabled further outreach. The journal is now linked to the newly established Interdisciplinary Center for Ecosystem Services and Biodiversity (ICEB) at Carinthia University of Applied Sciences (CUAS) (Figure 2).

It is increasingly important that editors, authors, reviewers, and of course our readers utilize a shared foundation and common understanding. This applies to data protection and ethics: assessing whether open data sharing could put rare species at risk; compliance with legal requirements; and how societal regulations (such as species and animal protection) should be taken into account and presented in submitted contributions. We must also address the use of artificial intelligence: in what ways and to what extent should AI be permitted in articles, and how should its use be disclosed? These are among the questions our Editorial Board will consider in forthcoming workshops, alongside many operational and technical matters.

Stable terminology and clear classifications are the foundation of scientific order. We aim to bring that clarity to our journal. As Carl Linnaeus famously stated, "Nomina si pereunt, perit et cognitio rerum" ("If the names are lost, the knowledge of things is lost"). As a starting point to promote gradual harmonization of terminology, we propose the following definitions and taxonomy for authors' optional use in *Carinthia Nature Tech.*

Fig. 2

Figure 2:
New visual identity. The brochure for *Carinthia Nature Tech*–part of a new brand presence–was designed locally by a young agency (LoMa Medien & Dienstleistungen OG, Velden am Wörthersee). The graphic features a stylized photo of a vegetation survey at the Nunatak Kleiner Burgstall (Glockner Group, Hohe Tauern National Park). It presents the journal's thematic focus and scientific standards: double-blind peer review; fully Open Access; published in English; no article processing charges. The invitation to all those interested: Discover *Carinthia Nature Tech*. Read. Submit. Review. Collaborate. (Graphic: LoMa, based on a photo by Vanessa Berger).

Abbildung 2:
Neues Erscheinungsbild. Der Folder zur Carinthia Nature Tech–Element eines neuen Auftritts–wurde von einer lokalen jungen Agentur (LoMa Medien & Dienstleistungen OG, Velden am Wörthersee) gestaltet. Die Grafik zeigt das verfremdete Foto einer Vegetationserhebung am Nuntak Kleiner Burgstall (Glocknergruppe, Nationalpark Hohe Tauern). Dargestellt sind der inhaltliche Schwerpunkt sowie die wissenschaftlichen Standards des Journals: Doppelblinde Begutachtung; vollständig Open Access; erscheint auf Englisch; keine Publikationsgebühren. Es ergeht die Einladung an alle Interessierten: Carinthia Nature Tech entdecken. Lesen. Einreichen. Begutachten. Zusammenarbeiten. (Grafik: LoMa, basierend auf Bild von Vanessa Berger).

We use *Nature Techs* as an umbrella term for technologies that sense, measure, analyze, and support the management of natural phenomena–both biotic (living) and abiotic (non-living). *Nature Techs* can be grouped by technology type and by application.

We distinguish three categories of technology:

BiDiTechs (Biodiversity Technologies). *BiDiTechs* are designed to detect, identify, and monitor biodiversity at taxonomic and functional levels. Examples include acoustic sensors and classifiers, camera traps coupled with computer vision, metabarcoding of samples collected from the environment, bio-logging and GPS collars, crowd-sourced observation platforms, and ecological modeling and annotation tools.

EnviTechs (Environmental Monitoring Technologies). *EnviTechs* measure and monitor non-living components of the environment. Examples include weather stations and microclimate sensors, hydrological monitoring systems, soil moisture and nutrient probes, and air and water quality monitors.

Management Apps (Management and Operations Applications). *Management Apps* are software tools that support the planning, execution, monitoring, and evaluation of management actions. Examples include *EarthRanger*, *SMART Connect*, the *IPAM Toolbox*, spatial planning tools, and integrated management and monitoring dashboards. Various dashboards or platforms fall into this category, for example iNaturalist and BirdNET.

We propose that monitoring of human activities specifically fall under *Management Apps*–for example, visitor monitoring tools. Systems for documenting poaching incidents, roadkill, or light pollution are also included here.

Application domains. This term refers to where these technologies are used. The nomenclature of a study should follow the conventions of the relevant domain. Illustrative domains include smart farming (digital agriculture), digital forestry, and conservation technologies. The latter subsumes all technologies employed in service of typical conservation objectives, such as biodiversity conservation, habitat protection, ecological restoration, and protected area management.

The path is made by walking. We recognize that these definitions are still evolving. We warmly invite our authors to engage with these provisional definitions to promote common understanding as we proceed in the current digital transformation.

The current issue exemplifies many ways that biodiversity can be observed. In the peer-reviewed sections, engagement of young scientists is visible through an information technology internship program that occurred at University of Klagenfurt. Analysis of long-term camera trap survey data reveals presence of non-target mammals and birds in Carinthia. Trends of visitor activity are documented through a GPS tracking survey in a Carinthia trans-boundary UNESCO GeoPark. In the Short Notes, results of land use change in an Ethiopian biosphere reserve are documented using satellite remote sensing. Diverse ways to monitor local agrobiodiversity are showcased. Lastly, two Book Reviews round out the issue, with one review on grasshoppers of Carinthia, and one review on the habitats of Europe.

Lastly, attentive readers will notice a novelty in this issue. For the first time, we include a Short Note contribution that examines the situation at Lake Tana Biosphere Reserve in the Amhara Region of Ethiopia. Our author guidelines state that: “The articles must have a clear connection to the Alps–Adriatic Region. At least one contributing author or the study area must be directly connected to the region.” In this case, the contribution arises from a long-standing collaboration between Bahir Dar University and CUAS, reflected in joint project endeavors by researchers from both institutions.

In this respect, too, it is our aim to develop common ground. We wish our readers fresh and engaging insights into current questions surrounding the development and application of *Nature Techs*.

Disclaimer: The authors affirm that all analyses, considerations, and representations reflect their personal knowledge and opinions. In this contribution, AI (*ChatBot Academic AI*) was used exclusively for translations and linguistic editing of the text. No generative AI tools were used. The authors remain fully responsible for the content, including any errors or omissions.

ABOUT THE AUTHORS

Susanne Aigner
Board member of Natural Science Association for Carinthia, Klagenfurt am Wörthersee, Austria, E-mail: office@oekologiebuero-aigner.com

Daniel Dalton
UNESCO Chair on Sustainable Management of Conservation Areas ICEB, CUAS Villach, Austria E-Mail: d.dalton@cuas.at

Michael Jungmeier
UNESCO Chair on Sustainable Management of Conservation Areas ICEB, CUAS Villach, Austria E-Mail: m.jungmeier@cuas.at

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Full Articles

Interdisciplinary approaches exploring the connection between biology and technology through slime mold simulation

Kristina Wogatai, Viviane Elmenreich, Anastasia Pulvermacher, Wilfried Elmenreich

ABSTRACT

Slime molds are fascinating organisms that, despite their name, are not fungi but amoeboid protists. Among them, the plasmodial slime mold *Physarum polycephalum* forms a multinucleate syncytium, known as the plasmodium, through repeated nuclear divisions without cytokinesis. In this phase, the organism appears as a viscous network-like mass containing millions of nuclei and is capable of solving complex tasks, such as navigating mazes, through self-organized behavior. Additionally, *P. polycephalum* is easy to culture and handle, making it an ideal model organism for studying self-organization, adaptive behavior, and biological network formation. The Smart Grids research group in the Department of Networked and Embedded Systems (NES) at the University of Klagenfurt conducts research involving slime molds. Specifically, the group investigates the potential of self-organizing applications in energy networks.

In cooperation with the Austrian Research Promotion Agency (FFG), the Faculty of Technical Sciences at the University of Klagenfurt offers Austrian students aged 15 and older the opportunity to gain insight into university-level research through a four-week summer internship. The project "Experiments with Slime Molds" was offered for the second time in 2024 by the Smart Grids research group. This interdisciplinary project allows participants to explore the intersection of biology and computer science. The internship offers participants the chance to explore the interfaces between biology, computer science, and mathematics. It is especially aimed at students interested in biological systems, the application of mathematical models, and the development and use of software tools for simulating natural phenomena. The interns begin by cultivating slime molds in Petri dishes and then simulate their behavior using SISMO (Simulation of Slime Molds), a tool developed by the Smart Grids group.

This article explores how biology and technology were combined in a four-week internship program and provides insights into the individual experiments conducted. A central element is the report by intern Viviane Elmenreich, who shares her experiences from the 2024 IT internship at the University of Klagenfurt. The focus of the internship was on biological experiments with the slime mold *P. polycephalum*, including the cultivation and reactivation of sclerotia, analysis of information processing within the plasmodium, and observations of behavioral and color response to stimuli. These experiments were complemented by technical components, such as programming a Raspberry Pi to automate time lapse photography and using the simulation tool SISMO to model slime mold behavior. The results demonstrated that slime molds are capable of absorbing information from their environment, processing dyes from food sources, and finding efficient paths to nutrients, both in physical experiments and in simulated environments. Furthermore, the combination of hands-on and digital approaches enabled deeper insights into the principles of biological self-organization. The internship not only contributed to the development and refinement of the SISMO simulation tool but also played a key role in enhancing the scientific education of the participants. The students gained valuable skills in experimental biology, programming, documentation, media production, and interdisciplinary research. These experiences fostered scientific thinking and also served as a strategic investment in talent development and in strengthening the University of Klagenfurt's position as an innovative research institution.

KEYWORDS

- Biology
- Slime Molds
- Simulation
- Self-Organizing Systems
- Interdisciplinarity
- Nature-based Algorithm
- *Physarum polycephalum*
- Science Communication
- IT Internship

Interdisziplinäre Ansätze zur Erforschung der Verbindung zwischen Biologie und Technologie durch Schleimpilzsimulation

ZUSAMMENFASSUNG

Schleimpilze sind faszinierende Organismen, die trotz ihres Namens keine Pilze, sondern amöboide Protisten sind. Unter ihnen bildet der plasmodiale Schleimpilz *Physarum polycephalum* durch wiederholte Kernteilungen ohne Cytokinese ein vielkerniges Synzytium, das sogenannte Plasmodium. In dieser Phase erscheint der Organismus als zähflüssige, netzwerkartige Masse mit Millionen von Zellkernen und ist in der Lage, durch selbstorganisiertes Verhalten komplexe Aufgaben zu lösen, beispielsweise das Navigieren durch Labyrinthe. Darüber hinaus lässt sich *P. polycephalum* einfach kultivieren und handhaben, wodurch es sich ideal als Modellorganismus für die Erforschung von Selbstorganisation, adaptivem Verhalten und biologischer

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Netzwerkbildung eignet. Auch die Forschungsgruppe Smart Grids des Instituts für Vernetzte und Eingebettete Systeme (NES) an der Universität Klagenfurt beschäftigt sich mit Forschung rund um Schleimpilze dieser Art. Konkret beschäftigt sich die Forschung in der Smart Grids Gruppe mit der Frage nach dem Potential selbstorganisierter Anwendungen in Energienetzen.

Die Fakultät für Technische Wissenschaften der Universität Klagenfurt bietet in Zusammenarbeit mit der Österreichischen Forschungsförderungsgesellschaft mbH (FFG) österreichischen Schülern und Schülerinnen ab 15 Jahren die Möglichkeit, im Rahmen eines 4-wöchigen Ferialpraktikums Einblicke in die Forschung an der Universität Klagenfurt zu erhalten. Das Projekt „Experimente mit Schleimpilzen“ wurde 2024 zum zweiten Mal in der Forschungsgruppe Smart Grids angeboten. In diesem interdisziplinären Projekt beschäftigen sich die Praktikant:innen mit einer Kombination aus Biologie und Informatik. Sie arbeiten zunächst mit Schleimpilzen, die in Petrischalen kultiviert werden, und simulieren anschließend deren Verhalten mit dem in der Smart Grids Gruppe entwickelten Tool SISMO (Simulation of Slime Molds). Das Praktikum bietet den Teilnehmer:innen die Gelegenheit, die Schnittstellen zwischen Biologie, Informatik und Mathematik zu erkunden. Es richtet sich insbesondere an Schüler, die Interesse an biologischen Systemen, der Anwendung mathematischer Modelle und der Entwicklung sowie Anwendung von Softwaretools zur Simulation natürlicher Phänomene haben.

Dieser Artikel beleuchtet, wie in einem 4-wöchigen Praktikum Biologie und Technik miteinander vereint werden und gibt einen Einblick in die einzelnen Experimente. Ein weiterer zentraler Punkt ist ein Bericht der Ferialpraktikantin Viviane Elmenreich, die ihre Erfahrungen im IT-Ferialpraktikum 2024 teilt. Dabei werden nicht nur die praktischen Versuche mit dem Schleimpilz *P. polycephalum* dargestellt, sondern auch deren wissenschaftliche Bedeutung sowie die strategische Relevanz des Praktikums für die Universität Klagenfurt herausgearbeitet. Im Mittelpunkt des Praktikums standen biologische Experimente zur Kultivierung und Reaktivierung von Sklerotien, zur Informationsverarbeitung im Plasmodium sowie zur Färbung und Verhalten von Schleimpilzen. Diese Versuche wurden durch technische Komponenten ergänzt, etwa die Programmierung eines Raspberry Pi zur automatisierten Bildaufnahme und die Arbeit mit dem Simulationstool SISMO zur Modellierung von Schleimpilzverhalten. Die Ergebnisse zeigen, dass Schleimpilze in der Lage sind, Informationen über ihre Umgebung aufzunehmen, Farbstoffe zu verarbeiten und effiziente Wege zu Futterquellen zu finden, sowohl in der realen Umgebung als auch in simulierten Szenarien. Zudem wurde deutlich, wie sich Experimente und digitale Modellierung gegenseitig ergänzen können, um biologische Selbstorganisationsprozesse besser zu verstehen. Das Praktikum trug nicht nur zur Weiterentwicklung des Simulationstools SISMO bei, sondern stärkte auch die wissenschaftliche Ausbildung der Teilnehmerinnen. Die Schülerinnen entwickelten Kompetenzen in experimenteller Biologie, Programmierung, Dokumentation, Medienproduktion und interdisziplinärer Forschung. Diese Erfahrungen fördern nicht nur das wissenschaftliche Denken, sondern leisten auch einen strategischen Beitrag zur Nachwuchsförderung und Positionierung der Universität Klagenfurt als innovativen Forschungsstandort.

INTRODUCTION

Physarum polycephalum is widely used as a model organism in biological and computational research due to its self-organizing behavior, adaptive network formation, and ability to solve complex optimization problems. Studies have shown that *P. polycephalum* can find efficient paths through mazes [1], develop robust and cost-efficient transport networks [2], and form structures comparable to real-world infrastructure systems such as railway networks [3]. These properties make *P. polycephalum* particularly interesting for research in unconventional computing, optimization, and bio-inspired network design.

These unique properties also make *P. polycephalum* an ideal organism for interdisciplinary educational projects combining biology, mathematics, computer science, and engineering. Based on this research background, the project “Experiments with Slime Molds” was announced as part of the IT internships as follows: “Slime molds are highly interesting creatures. Contrary to what the name suggests, *P. polycephalum* is not a fungus but a plasmodial slime mold that exists as a multinucleated syncytium formed through repeated nuclear divisions without cytokinesis. Slime molds can be used in experiments to solve labyrinths and for network planning. In this practical course, you will work with slime molds in Petri dishes and with a tool that simulates the special behavior of slime molds. Physical obstacles (mountains, lakes) and labyrinths can also be modeled with the help of 3D printing. You should have an interest in biology, mathematics, computer science and scientific experiments".

In the end, the two interns Viviane Elmenreich and Anastasia Pulvermacher were selected from several applications, both of whom had excellent grades and promising CVs. Both of them attended an academic secondary school (AHS) in Klagenfurt. While their education did not include formal technical training, they exhibited a strong interest in and basic understanding of technological concepts.

Objectives and Learning Outcomes for Interns

The internship offers participants an initial insight into studying and working at an Austrian university. For many, it is also their first experience with academic work and research. Through close interaction with their supervisors, participants gain an authentic impression of everyday university life and research work. In the field of technical sciences in particular, the internship provides an opportunity to experience complex technical issues practically and to become familiar with interdisciplinary approaches. In the current study, working with the biological system *P. polycephalum* and computer-aided simulations of its behavior enabled interns to develop a deeper understanding of scientific and technical issues. Participants were provided opportunities to develop a better understanding of self-organizing processes and acquire basic skills in applying computer-aided methods to analyze complex biological systems.

Research Benefits

An important, research-oriented objective of the internship was to evaluate the existing simulation tool SISMO (Simulation of Slime Molds) [4], [5] in a practical setting. The project involved students with varying levels of prior experience, creating an ideal setting to assess the tool's usability, clarity, and flexibility. Through hands-on use and feedback from the interns, potential weaknesses in the interface, functionality, and underlying algorithm were identified. These insights were useful for the tool's future development, contributing to its refinement and applicability in future research and educational contexts. Another aim was to carry out several in vitro experiments whose results could potentially help answer specific research questions. Current investigations, for example, focus on the mechanisms of information dissemination within the slime mold network. Analyzing the uptake and transmission of dyes during dispersal and feeding provided a method to visualize and better understand the processes of information transfer within the network.

Experiment Overview

A series of tasks to be completed during the four-week internship was discussed in advance. These experiments aimed to develop a deeper understanding of slime mold behavior under different conditions and explore slime mold problem-solving abilities. The experiments also demonstrated how slime molds react to various external stimuli and the mechanisms they use to adapt and solve problems. Alongside the in vitro experiments, simulations were carried out with SISMO. The work was documented daily, and progress was presented regularly. A video was made about the internship work. Table 1 provides an overview of the experiments that were planned and prepared before the internship. A detailed description of the tasks carried out can be found in the Methods section.

Tab. 1

Experiments and Tasks
Reproduction of Slime Molds
Influence of Food Colors on Slime Molds
Color Merging within the Slime Mold Network
Slime Molds in Mazes
Regeneration and Healing
Simulations with SISMO
Multimedia Production
Documentation and Reporting
Research and Theoretical Study

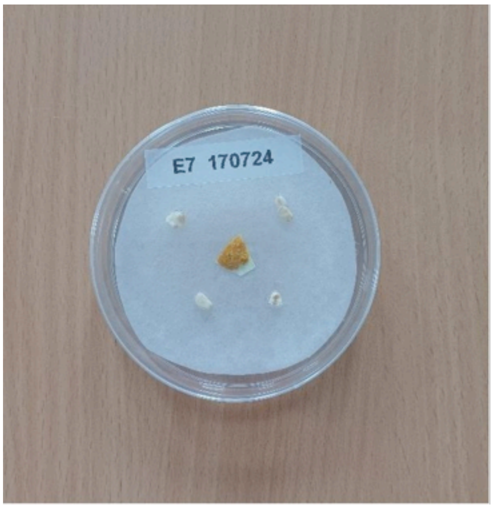
Table 1: Overview of Experiments and Tasks during the Internship

Tabelle 1: *Übersicht über Experimente und Aufgaben während des Praktikums*

EXPERIMENTAL ANALYSIS OF LIVING SLIME MOLDS

Reproduction of Slime Molds

In one of the first experiments, a slime mold sclerotium was placed on moistened filter paper in a Petri dish containing Sabouraud 2% glucose agar as a nutrient medium and oat flakes as nutrient hot spots. Within a few days, active growth toward the placed oat flakes was observed. The slime mold formed a fine network, clearly separated from the original sclerotium. Parts of the grown plasmodium were later cut out and left to dry in order to produce new sclerotia. However, these were not always successfully reactivated. It was assumed that the amount of active slime mold material on the filter paper was insufficient to enable reactivation. A particularly striking example of successful reproduction was seen in another experiment. Here, a sclerotium was again placed on filter paper with nutrient medium and oat flakes. Over several days, the slime mold developed very actively, connecting all the oat flakes in the Petri dish within a dense network, eventually growing over the edge into neighboring dishes and even onto the surface of the storage cabinet. Parts of this plasmodium were removed and specifically dried to produce new sclerotia. Toward the end of the experiment, it was observed that the slime mold might have begun forming fruiting bodies in what could be an indication of another possible reproductive pathway. Targeted experiments for producing new sclerotia were also carried out, in which parts of an active plasmodium were directly dried on filter paper. Some of these sclerotia showed minimal activity even after the drying process had begun, before eventually becoming completely dormant. These experiments demonstrated that slime molds are generally capable of entering a sclerotial state through controlled drying, allowing for its potential long-term preservation. The experiments also showed that the substrate plays a crucial role. While cultivation on filter paper was mostly successful, cultures without filter paper were more prone to mold contamination or showed little to no growth. This suggests that filter paper is beneficial for regulating moisture and maintaining favorable conditions for reproduction. Figure 1 shows one of the experiments carried out to reproduce slime molds. In summary, reproduction of slime molds through sclerotia is a robust and effective mechanism for ensuring the long-term survival of these organisms. Through targeted cultivation, drying, and rehydration, slime molds can be reused and reactivated multiple times, provided there is enough active material and suitable environmental conditions.



Reproduction of Slime Molds: Day 1

Reproduction of Slime Molds: Day 2

Reproduction of Slime Molds: Day 3

Reproduction of Slime Molds: Day 6

Fig. 1

Figure 1: Experiment: Reproduction of Slime Molds

Abbildung 1: *Experiment: Vermehrung von Schleimpilzen*

Influence of Food Colors on Slime Molds

A suite of experiments investigated whether the slime mold *P. polycephalum* absorbs food dyes and how these dyes influence its growth behavior. The dyes are also used to visualize the growth pathways. Petri dishes with a layer of solidified agar-agar served as the experimental setup. Circular filter paper was placed on the agar to improve moisture distribution. The slime mold sclerotia were placed in the center of the dish on the moist filter paper and lightly moistened with sterile water to reactivate them. To prepare food sources, oat flakes were treated with various food dyes that were applied with a pipette. The oat flakes were dried to prevent the color from spreading uncontrollably on the agar. The colored oat flakes were then arranged evenly, two to three centimeters apart, around the slime mold.

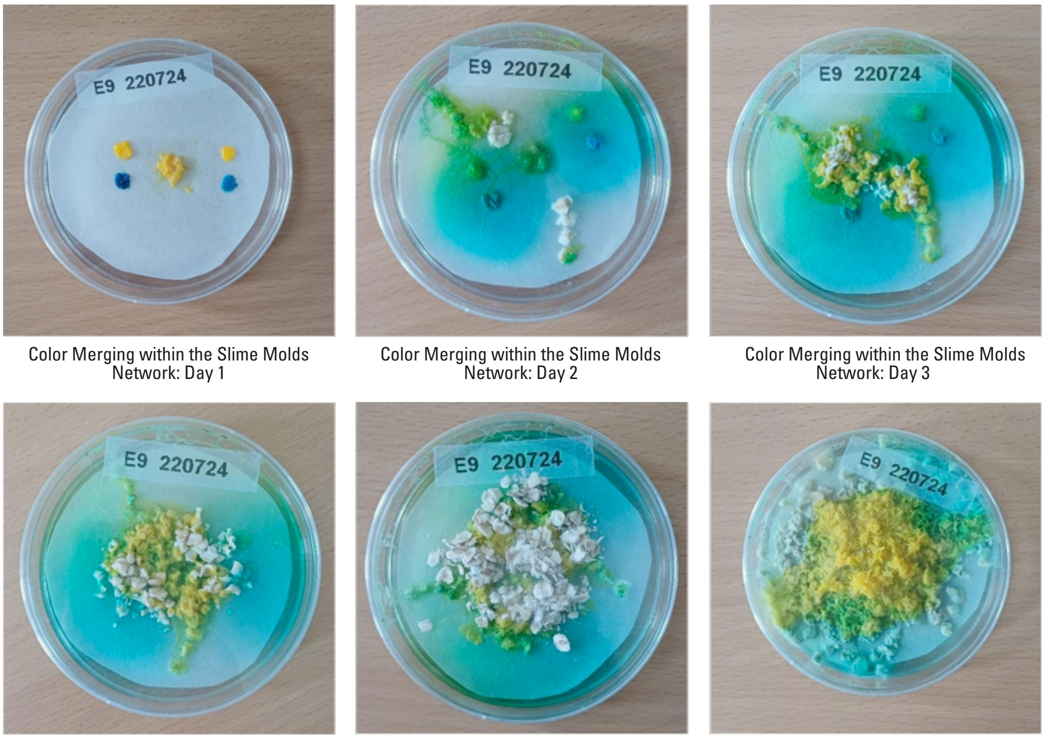
The spread of the slime mold was observed and documented over the course of several days. Daily camera recordings and microscopic images were used for analysis. Specifically, we recorded which colored food sources were reached, whether there was a preference or avoidance of certain colors, and if the organism took up color. A microscope was used to check for structural or color changes in the slime mold resulting from dye uptake. Additionally, the growth structures revealed by dyes (e.g., pseudopodia and tube networks) were examined for their shape, branching, and orientation. It was hypothesized that the slime mold would actively move toward the dyed oat flakes. Partial dye uptake by the organism appeared possible and manifested as slight color changes. Further studies would supplement this setup with other environmental factors, such as light, temperature, or humidity, to analyze interactions between chemical and physical stimuli. Additionally, using several dyes simultaneously would open up the possibility of recording the behavior of *P. polycephalum* in more complex decision-making situations.

The aim of the two experiments, *Colored Oat Flakes 1* (blue and red) and *Colored Oat Flakes 2* (black and pink), was to investigate whether and how slime molds absorb dyes from colored food sources and whether this affects the color of the plasmodium. In the first experiment, the slime mold clearly responded to the red oat flakes. By the second day, it had started to grow toward it and had eventually consumed it. Over the following days, the plasmodium took on an orange-reddish hue, indicating that the dye had been absorbed and distributed throughout the organism. Although there were no further changes after that point and the slime mold eventually dried out due to low humidity, a noticeable color change was observed. In the second experiment, the slime mold initially spread in two directions, toward a black oat flake and a non-dyed one. Over time, it showed a preference for the colorless oat flake, consuming them and continuing to be fed non-dyed food. No clear and consistent color change was observed. However, later in the experiment, it was noted that the section of the plasmodium near the pink oat flake had taken on some of its color, while the rest of the organism remained yellow. Overall, the experiments showed that *P. polycephalum* is capable of absorbing dyes from colored food, though the extent and uniformity of the color change depend on the specific dye and the feeding behavior of the slime mold. A uniform color shift across the entire plasmodium was only clearly observed in the experiment involving the red oat flake. In both cases, it was also observed that overly moist conditions increased the risk of mold contamination, influencing the outcome of the experiments.

Color Merging within the Slime Mold Network

This experiment investigated how the slime mold *P. polycephalum* takes up and merges food dyes when exposed to differently colored nutrient sources. Unlike animals, slime molds lack specialized transport systems, such as blood vessels. Instead, nutrients and potential dyes are absorbed across their entire body and distributed via cytoplasmic streaming. Consequently, when exposed to two distinct dyes, color merging may occur, particularly in regions where slime mold networks merge. The experimental setup consisted of Petri dishes containing solidified agar with cut filter paper on top to enhance moisture retention. Reactivated *Physarum* sclerotia are placed in the center of the moistened filter paper. Blue and yellow food colorings were used to dye oat flakes, which were then allowed to dry to prevent dye diffusion on the agar. The flakes were arranged on opposite sides of the Petri dish, approximately 2–3 cm from the slime mold. The slime mold's growth and expansion were monitored daily with photographic and video documentation focusing on dye uptake and the formation of colored pathways. Intersections of differently colored slime mold networks were examined microscopically to detect potential color changes indicative of dye merging (e.g., green resulting from blue and yellow). The null hypothesis was a lack of dye merging, which is manifested as distinct color regions due to limited internal transport, and the alternate hypothesis was partial dye merging, which would be observable as new colors at network intersections reflecting intracellular transport and fusion of dyes. The analysis involved a detailed assessment of color distribution and merging patterns to elucidate the mechanisms by which dyes are transported within the slime mold.

The experiment focused on how the slime mold responds to the simultaneous intake of two differently colored oat flakes, specifically, one blue and one yellow. The aim was to establish whether the colors would blend within the plasmodium or remain confined to the points of contact. On the first day, the slime mold exhibited initial activity and started to grow toward the colored oat flakes. By the second day, it had consumed both the blue and yellow flakes. Consequently, the entire slime mold network turned green, indicating that it had absorbed and merged the dyes, distributing the combined color throughout its body. Over the following days, the slime mold was fed uncolored oat flakes. It was observed that the previously green branches began to retract and that newly formed areas of the plasmodium returned to their original yellow color. This suggests that the dye was either broken down or diluted over time through the growth of new, undyed tissue. Overall, the experiment demonstrated that *P. polycephalum* was capable of absorbing and merging food dyes within its network, and that this coloration was reversible when uncolored food was introduced. Additionally, time lapse imaging offers dynamic insights into the progression of dye transport and merging over time. Figure 2 shows the progress of the experiment.



Color Merging within the Slime Molds Network: Day 1

Color Merging within the Slime Molds Network: Day 2

Color Merging within the Slime Molds Network: Day 3

Color Merging within the Slime Molds Network: Day 4

Color Merging within the Slime Molds Network: Day 5

Color Merging within the Slime Molds Network: Day 8

Fig. 2

Figure 2: Experiment: Color Merging within the Slime Molds Network

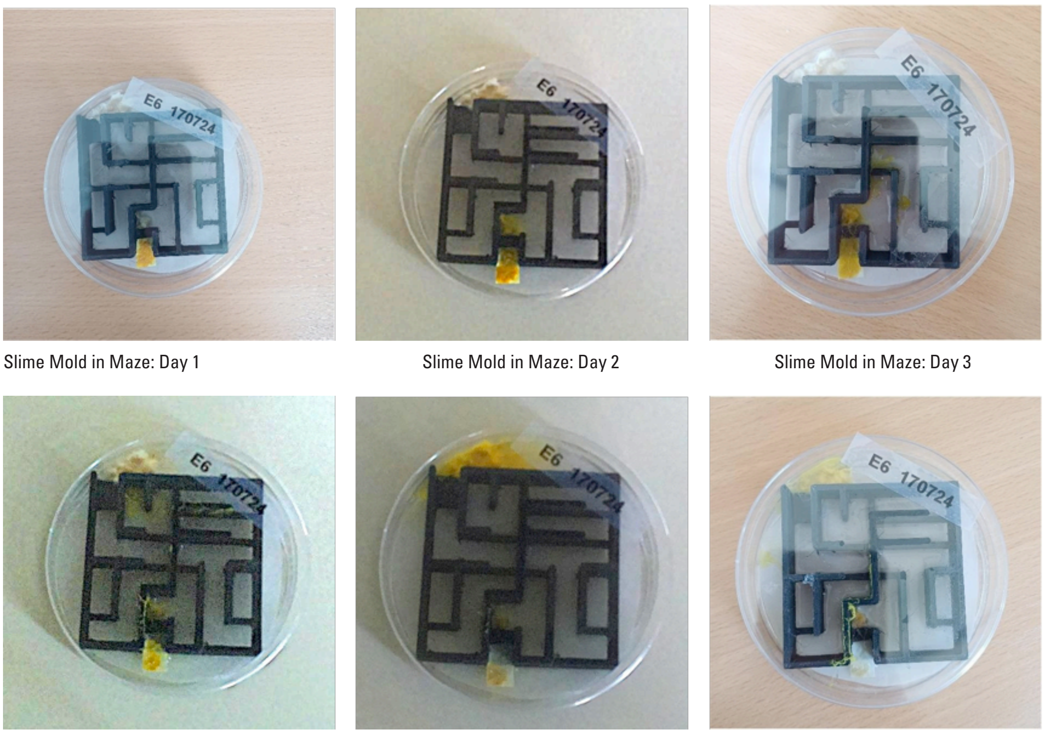
Abbildung 1: *Experiment: Farbvermischung im Schleimpilznetzwerk*

Future work will explore additional dye combinations, such as red and blue or red and yellow, to evaluate the generalizability of color merging behavior. Since different food colorings contain distinct chemical compounds and pigments, future studies should also investigate whether the observed responses of *P. polycephalum* depend on the chemical composition of the dyes rather than color alone.

Slime Molds in Mazes

This experiment combined in vitro experiments with 3D design and 3D printing. The task was to design a maze whose entrances and exits are clearly defined and to create it using a 3D printer. It was possible to delegate this task to a student who performed an internship on the subject of 3D printing. The experiment used slime mold cultures, a 3D-printed maze, Petri dishes with agar-agar, oatmeal as a food source, filter paper, a microscope with a camera, sterile water, a timing device (e.g., stopwatch) and documentation tools such as a notebook and a camera. The printed maze was positioned on a Petri dish prepared with agar-agar and filter paper, and a slime mold was applied at the maze entrance. A small quantity of moist oat flakes was placed at the end of the maze. The growth of the slime mold through the maze was observed and the time taken by the organism from the entrance to the exit measured.

The hypothesis that slime molds are able to demonstrate their ability to solve problems is justified by the expectation that they will find the shortest or most efficient path to the food source. Slime trails were expected to be achieved, representing pathway marking. The recorded times and paths should provide valuable information about the subjects' navigation and decision-making behavior. Daily monitoring was used to document progress, whereby the filter paper was constantly supplied with moisture to ensure optimum growth conditions. The measurements of time and path allowed conclusions to be drawn about the navigation strategies of the slime mold. Optionally, the oat flakes could be dyed with food coloring at the exit to make the path of the slime mold more visible. Figure 3 shows the results of the experiment.



Slime Mold in Maze: Day 1 | Slime Mold in Maze: Day 2 | Slime Mold in Maze: Day 3

Slime Mold in Maze: Day 4 | Slime Mold in Maze: Day 5 | Slime Mold in Maze: Day 6

Fig. 3

Figure 3: Experiment: Slime Molds in Mazes

Abbildung 3: *Experiment: Schleimpilze in Labyrinthen*

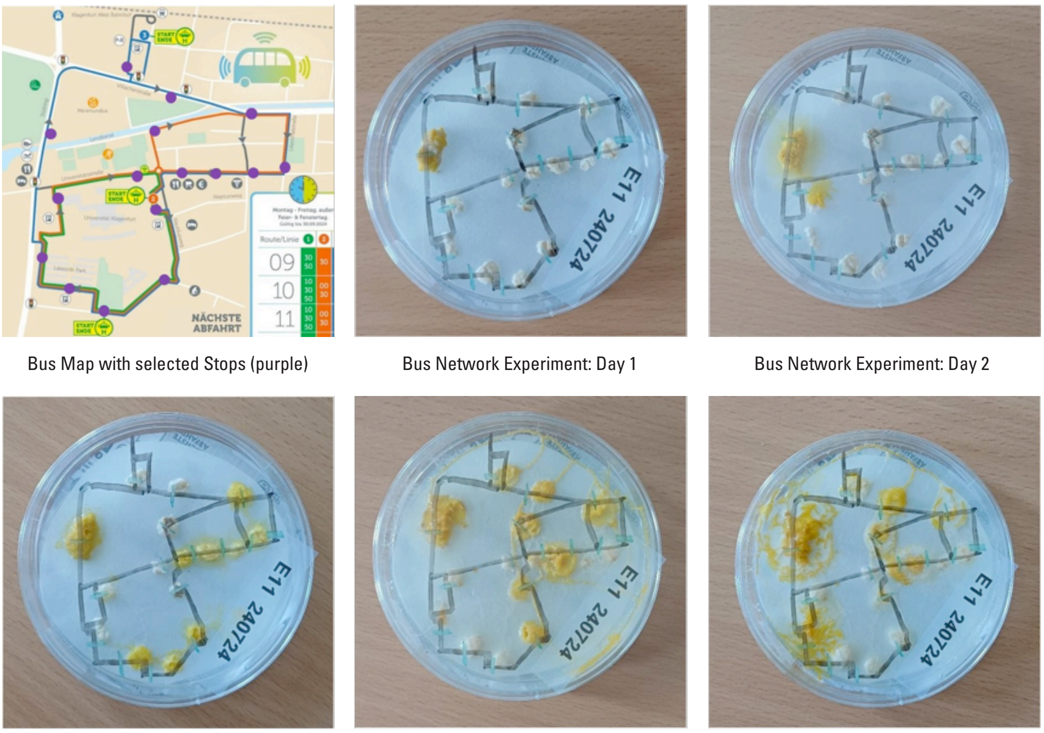
The extension of the object of investigation includes the use of more complex maze designs to further evaluate problem-solving skills. In addition, the influence of different environmental conditions, such as light, humidity, and temperature on maze traversal was investigated. Several food sources were placed in the maze in order to observe the navigation behavior with competing targets.

Regeneration and Healing

This experiment investigated the ability of slime molds to regenerate damaged or divided structures. It was hypothesized that slime molds demonstrate a remarkable ability to regenerate by rapidly reconnecting damaged or divided parts into a complete organism. The duration of regeneration would vary depending on factors such as the size of the divided pieces and environmental conditions. A Petri dish with solidified agar-agar was prepared, and a healthy slime mold culture was carefully cut into several pieces using a scalpel or sharp knife. The divided slime mold pieces were then placed close together on the agar surface in the Petri dish, allowing them to come into contact with each other. Throughout the experiment, the regeneration process was observed daily, and the time required for the divided pieces to grow back into a complete slime mold was recorded. Photos or videos were regularly taken to document the development. The Petri dish was kept moist at all times to ensure optimal growth conditions. The regeneration time was measured for each divided piece, and microscopic examination of the regenerated areas was conducted to assess precisely how regeneration occurs and whether there are any structural differences compared to the original state.

Bus Network

The two interns independently designed and carried out another experiment based on their own idea. This experiment aimed to investigate whether *P. polycephalum* would form a network between selected locations resembling the route map of the autonomous shuttle system operating in Klagenfurt. Out of the 18 total stops, 16 shuttle stops were selected and represented as nodes on an experimental substrate; each node was marked with a food source to attract the slime mold. The hypothesis was that the resulting network structure would differ significantly from the actual shuttle route, since the slime mold is not constrained by infrastructure such as roads or traffic regulations. This exploratory experiment provided insight into the differences between human-engineered transportation networks and those emerging from self-organizing biological systems and offered a new approach to analyzing biologically inspired optimization strategies. In her internship report, Viviane Elmenreich summarized the procedure and observations of the experiment as follows: On the first day of the experiment, a Petri dish was prepared



Bus Map with selected Stops (purple) | Bus Network Experiment: Day 1 | Bus Network Experiment: Day 2

Bus Network Experiment: Day 3 | Bus Network Experiment: Day 6 | Bus Network Experiment: Day 10

Fig. 4

Figure 4: Bus Network Experiment

Abbildung 4: *Experiment: Busnetzwerk* with agar-agar and filter paper. A printed image of the bus network was attached to the underside of the dish and a diagram was drawn on the lid. The selected 16 stations were marked on the filter paper and oat flakes were placed on them. Part of a slime mold from a previous experiment was added to the dish. The dish was then stored in the dark. The very next day, the slime mold began to spread and reach the oat flakes. Over the following days, it continued to grow, connecting several stations. The experiment was completed on day seven. By this time, the slime mold had formed its own network, which did not correspond exactly to the original bus network. Notably, many connections ran along the edge of the Petri dish instead of taking the shortest route. Figure 4 shows photographic documentation of the experiment.

SIMULATIONS WITH SISMO

In this task, the interns worked with the simulation tool SISMO, which is used to model the behavior of slime molds. They compared the resulting simulations with experimental data to evaluate the accuracy and reliability of the model. They also familiarized themselves with the NetLogo programming language in order to subsequently expand SISMO. The goal was to adapt the tool to specific experiments in order to achieve the most accurate possible representation of the actual behavior of slime molds.

The simulation tool SISMO was used to model the specific behavior of slime molds during foraging and network planning. The simulation results were subsequently compared with experimental data. Initially, it was ensured that the SISMO software was installed on the computer and that the basic functions and user interface of the tool were understood. Data from the conducted experiments, such as growth times, paths, and color mixtures, were collected and documented. A new simulation project was then created in SISMO, and the parameters from the experiments, including the positions of food sources, environmental conditions, and maze designs, were defined. The simulations replicate the behavior of slime molds during foraging and network formation. The resulting simulation data were observed and recorded. These results were compared with actual experimental findings to identify similarities and differences in behavioral patterns, paths, and durations.

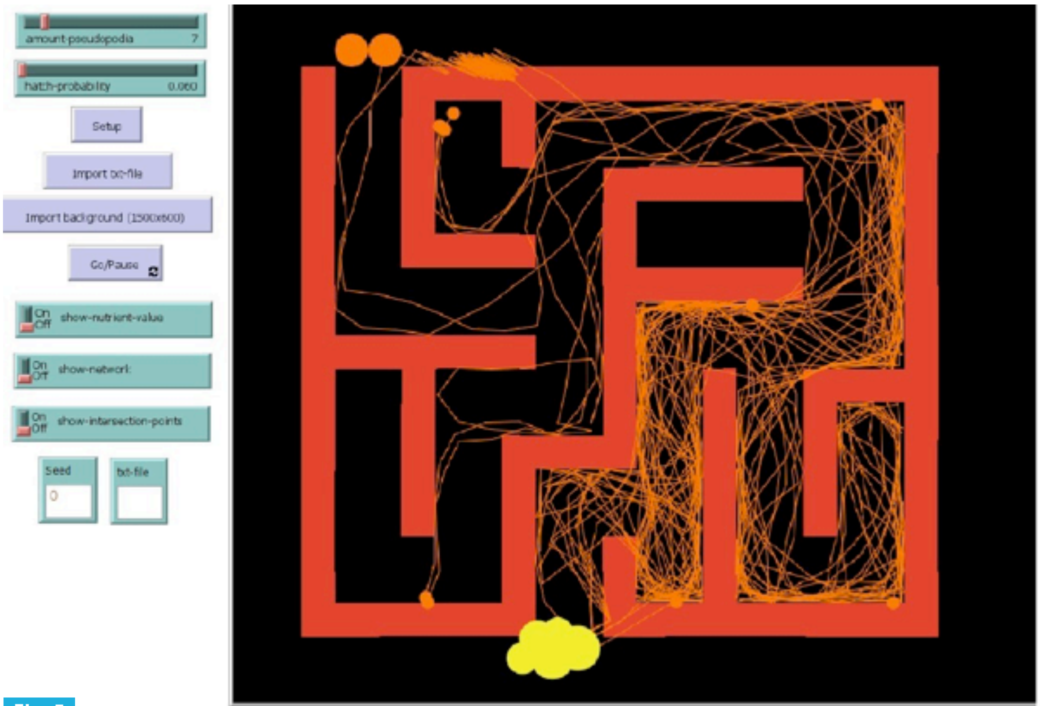


Fig. 5

Figure 5: SISMO Simulation of the Slime Molds in Mazes Experiment

Abbildung 5: *SISMO-Simulation des Schleimpilz-Labyrinth-Experiments*

Furthermore, the ability of the simulation to accurately reproduce observed color mixtures and regeneration processes was analyzed. All performed simulations and their outcomes were thoroughly documented, including screenshots and detailed notes on significant observations. For example, Figure 5 illustrates the maze experiment performed in silico as a SISMO simulation.

DOCUMENTATION

Multimedia Production

The tasks of multimedia production included the development of a concept for an informational video about slime molds, including the creation of a storyboard and a shooting schedule. Footage was then taken of slime molds as they grew and during various experiments. The collected material was then edited and supplemented with a suitable narrative. The aim of this task was to create a clear and informative video that conveys the characteristics and behavior of slime molds as well as the experiences gained during the internship. In addition, the interns learned how to use video editing software and thus expanded their technical skills in the field of media production.

Reporting

As part of the internship, participants kept a daily journal in which they recorded all activities and observations. In addition, they wrote weekly reports summarizing their progress and interim results. At the end of the internship, they prepared a comprehensive final report that documented all experiments conducted, their results, and key insights. The goal of this task was to develop skills in scientific documentation and structured reporting.

Research and Theoretical Study

Participants were tasked with conducting literature research on slime molds and their properties, summarizing recent scientific studies. They also focused on specific topics, such as the application of slime molds in energy technology, and prepared a presentation to share their findings. The goals of this task were to deepen theoretical knowledge and to enhance research and presentation skills.

RESULTS

The results are presented through three complementary perspectives: the learning outcomes achieved by the interns, the benefits generated for ongoing research, and the program's strategic relevance to the University of Klagenfurt. This differentiation enables a more nuanced analysis of the program's overall impact, highlighting its multifaceted value in educational, scientific and institutional terms.

Learning Outcomes for Interns

The internship program gave participating students the opportunity to develop a wide range of skills and gain experience in various fields. A key learning outcome was the practical execution of biological experiments, through which interns gained foundational knowledge of biology and experimental methodology. Using the SISMO simulation framework further provided hands-on training in information technology and computational modelling, encouraging interdisciplinary thinking at the intersection of biology and technology. Additionally, interns were actively involved in multimedia production, scientific documentation and structured research process reporting. These activities strengthened their communication skills and deepened their understanding of how to present complex information in an accessible way. Finally, independent study of the literature and theoretical engagement with the research topics fostered critical thinking and a reflective approach to scientific enquiry.

In the following report, Viviane Elmenreich, an intern, describes their personal impressions and the professional and practical experience they gained during her internship:

EXPERIMENTS ON PHYSARUM POLYCEPHALUM AT THE UNIVERSITY OF KLAGENFURT

> The experiments were conducted in July 2024 and focused on experimental work with *Physarum polycephalum*. The primary objective was to evaluate the organism's problem-solving capabilities by conducting independent experiments and establishing new sclerotia cultures for future use.
>
> Daily activities included the systematic observation of slime mold growth across all active Petri dishes, photographic documentation, and nutrient replenishment. Fungal contamination was recorded where present, and hypotheses were formulated to explain its occurrence. All observations and photographic evidence were incorporated into the project documentation on a daily basis.
>
> The first week was dedicated to an intensive literature review encompassing scientific papers, online resources, and video material on *P. polycephalum*, alongside experimental preparation. Media preparation involved cooking agar-agar, casting it into Petri dishes, and placing pre-cut filter paper on top. Sclerotium reactivation required ensuring adequate moisture and proximity to a food source. For more complex experiments, oat flakes were dyed with food coloring and a 3D-printed labyrinth was used as an experimental substrate, with the 3D printing carried out by a fellow intern.
>
> A Raspberry Pi was configured and programmed to photograph the slime mold in the maze at 30-minute intervals, with two LED lamps triggered at each capture. Due to insufficient illumination, the overnight photographs could not be utilized. The labyrinth experiment was additionally modelled in SISMO; the in vitro result — in which the slime mold grew along the walls to reach the food source — was not reproduced by the simulation, an observation with direct relevance to model refinement.
>
> Progress meetings were held at two-week intervals to review results and plan subsequent experiments. The internship concluded with the production of a short documentary film on the project. The practical work provided a foundation for scientific thinking and independent experimental methodology.

During their four-week internship at the University of Klagenfurt, the interns developed a wide range of skills in experimental biology, information technology and scientific communication. Working independently, they designed and conducted a series of experiments on *P. polycephalum*, focusing on the reactivation of sclerotia, behavioral observation and nutrient response. They gained practical experience in preparing media (agar-agar), maintaining cultures and documenting developmental stages through systematic photography. The internship also involved integrating a Raspberry Pi system to automate time-lapse photography and using SISMO, a simulation tool for modelling slime mold behavior. By comparing in vitro and in silico results, the interns developed a deeper understanding of the differences between experimental and simulated environments. Furthermore, the interns demonstrated their ability to work independently, formulate hypotheses and critically reflect on experimental outcomes. These activities strengthened their scientific reasoning and provided a foundational experience in


Setup of the Maze Experiment


Setup of the Color Merging Experiment

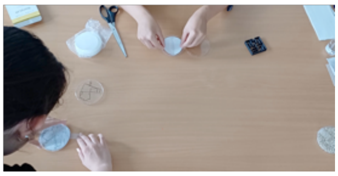

Setup of the Bus Experiment

Fig. 6

Figure 6: Interns performing various Experiments

Abbildung 6: *Praktikantinnen bei verschiedenen Experimenten*

interdisciplinary research, bridging biology and computer science. In addition, a video documenting the experimental process was produced as part of the internship. Not only were the experiments filmed, but the interns also wrote their own script to present the content in a structured way. The filming, some of which took place in a professional video studio, was planned and carried out independently. Through these tasks, the students acquired and deepened essential skills in media production, project organization, and professional presentation. In particular, creating the script independently and practically implementing the filming promoted an understanding of how to convey scientific content clearly and appealingly. Various studies, such as the study by Yael Wolinsky-Nahmias and Arthur H. Auerbach [6], show that internship programs of various designs can achieve a high level of impact and satisfaction if central elements are integrated accordingly. This is particularly true if they promote initiative, impart skills, and are experienced as meaningful. Figure 6 shows the interns performing various experiments.

Research Benefits

During the internship, the SISMO tool was systematically tested in a practical environment. The aim was to evaluate its user-friendliness, functionality, and scalability in real-world scenarios. Having students with different levels of technical knowledge use the application enabled a more detailed analysis of its usability. It was found that, in its previous form, SISMO could only be used intuitively to a limited extent by inexperienced users. The weaknesses identified related particularly to the user interface and initial control of simulation elements, such as placing food sources or starting points for slime mold networks. Subsequently, targeted improvements were made to increase accessibility and optimize the system for educational and teaching contexts in particular.

Additionally, the interns adapted and expanded the underlying code base to align it with specific experimental requirements. For instance, new dye models were integrated to simulate information transfer in the network, and the simulation system's existing behavioral rules were modified accordingly. These modifications were successfully implemented and tested, demonstrating their seamless integration with the existing system components.

Several in vitro experiments with *P. polycephalum* were conducted in parallel with the software development. These experiments aimed to observe the real-world behavioral patterns of the slime mold with regard to resource utilization, network expansion and transport processes, and to compare these with simulation results. One notable experimental setup involved selectively colorizing food sources to investigate how information is transmitted or replaced within the biological network. These data will serve as a foundation for the ongoing development of SISMO and are currently being used to simulate information propagation within the model.

Overall, the close interplay between experimental work and digital modelling has contributed to the further development of the simulation tool and deepened our understanding of self-organizing biological networks. The insights gained during the internship are currently informing ongoing research efforts and demonstrating the potential of SISMO as a tool for supporting data-driven modelling of bio-inspired systems.

Strategic Importance for the University of Klagenfurt

Zenobia Ismail's work [7] examines the advantages of internship programs, focusing on perceived improvements in skills and employment outcomes, particularly within the fields of information technology and business. It is shown that companies see interns as low-cost workers who can support them, especially during labor-intensive periods [8], and take on projects that would otherwise not be implemented [9]. Furthermore, internships can reduce long-term recruitment and training costs, as they act as a trial period that can lead to permanent employment [10], [11], [12]. The practical experience gained during an internship shortens the onboarding period for interns compared to that for new employees [12]. A student internship at a university, particularly in a technical or research-related field, offers the opportunity to recruit potential students at an early stage, rather than being focused on the immediate workload. Such internships give institutes the chance to get to know talented and interested young people, inspire them to study at their university, and introduce them to scientific work early on. If the interns later return as students, both parties benefit: the university gains committed young talent, and the students are already familiar with the processes and key contacts, making it easier for them to start working as a study assistant or tutor. In the long term, the mentoring effort pays off through the targeted promotion of young talent and stronger ties to the university.

A qualitative study by Saraiva et al. [13] further found that participants in research internships showed a strong subsequent willingness to pursue careers in STEM fields. Beyond recruitment, the internship also fosters sustainable networking between the university and the regional education sector, creating opportunities for future collaborations and strengthening the university's visibility as an innovative, socially responsible research institution.

Although no studies or concrete figures are yet available on how many former participants in the IT internship have subsequently decided to study at the Institute of Technical Sciences (TEWI) or at the University of Klagenfurt in general, there is nevertheless clear potential for an internship to arouse interest in technical fields of study at an early stage and thus contribute to the targeted recruitment of qualified young students.

DISCUSSION

The project *Experiments with Slime Molds*, supported within the 2024 IT Internship Programme at the University of Klagenfurt, which focused on experimental work with *P. polycephalum*, is a compelling example of how interdisciplinary research environments can promote pedagogical development, facilitate ongoing scientific research and contribute strategically to institutional objectives.

Case studies of comparable interdisciplinary research internships have shown that the combination of hands-on experimentation, guided reflection, and independent project work is particularly effective in developing scientific self-efficacy among secondary school participants [13]. The present case is consistent with these findings, illustrating how a structured four-week program can simultaneously serve educational, research-oriented, and institutional objectives.

One of the program's most important outcomes was the comprehensive learning experience it offered the interns. They participated in a variety of activities, ranging from hands-on biological experiments to computer modelling and media production. This allowed them to develop both hard and soft skills. Notably, they learned to independently plan, conduct and document experiments, work with living organisms, and handle scientific tools such as the SISMO framework and Raspberry Pi-based data acquisition systems. Throughout the internship, the participants deepened their understanding of biological systems and information transmission in slime molds, while also strengthening their critical and reflective thinking skills. Integrating theoretical knowledge, literature research and practical application fostered a well-rounded scientific mindset. Including multimedia elements, such as writing and producing a short film, added an important communicative dimension to the interns' experience, teaching them to convey complex scientific ideas clearly and creatively.

The internship also generated valuable insights for ongoing research projects. By systematically testing the SISMO tool, the interns helped to identify issues with the software's usability and limitations, particularly with regard to accessibility for inexperienced users. These findings informed targeted improvements to the tool's interface and functionality, particularly with regard to educational applications. The interns also contributed to the system's development by adapting code and incorporating new features, such as color-based data models that simulate information propagation in biological networks. The effectiveness of these enhancements was validated through parallel in vitro experiments, which offered direct comparisons between simulated and real-world slime mold behavior. This approach helped refine SISMO and generated new data for future bio-inspired modelling. For instance, the strategic use of experiments involving dyed oat flakes offered insights into how slime molds integrate and distribute information within their networks. This concept has broader implications for understanding self-organizing systems in both natural and artificial contexts.

Beyond its scientific and educational dimensions, the internship program supports the University of Klagenfurt's broader strategic objectives. As different studies have highlighted, internships serve as a valuable recruitment tool, offering universities the opportunity to attract motivated students at an early stage. By working on engaging, meaningful projects, young participants develop a connection with the institution that can lead to future enrollment, employment or long-term collaboration. In technical and research-focused fields in particular, internships act as trial periods, enabling both the institution and the intern to evaluate their long-term compatibility. Although concrete data on retention and enrollment outcomes is not yet available, the potential impact of these programs on university-community engagement and talent development is evident. By investing in structured, interdisciplinary internships like this one, the University of Klagenfurt strengthens its scientific output and reputation, actively contributing to the development of future researchers and innovators.

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ABOUT THE AUTHORS

Kristina Wogatai
Networked and Embedded Systems
University of Klagenfurt
Austria
kristina.wogatai@aau.at

Viviane Elmenreich
Klagenfurt, Austria

Anastasia Pulvermacher
Klagenfurt, Austria

Wilfried Elmenreich
Networked and Embedded Systems
University of Klagenfurt, Austria
wilfried.elmenreich@aau.at

BACK TO CONTENT

From wildlife management to biodiversity assessment: Using camera trap by-catch data to infer species richness

Stephanie Wohlfahrt, Horst Leitner

ABSTRACT

Camera traps are widely used in wildlife management to monitor focal species such as ungulates. However, the large amount of data on non-target species is rarely analyzed systematically. In this study, we examine whether management-oriented camera trap surveys can be used to infer broader biodiversity patterns. Using camera trap data from four study sites, we recorded 57 species, including 25 mammals and 32 birds. Species richness varied between sites but this was not primarily driven by total sampling effort. Despite substantially greater effort invested, a long-term opportunistic survey detected only slightly more species than a short-term survey using systematic random placement, consistent with spatial coverage, camera density and area size jointly influencing species detection rather than sampling duration alone. We analyzed species accumulation using Michaelis–Menten models fitted to taxa that could be reliably detected by camera traps. Systematic random surveys reached species saturation more rapidly and exhibited faster accumulation than opportunistic designs. The proportion of mammal species listed under the EU Habitats Directive remained consistent across sites, suggesting that camera traps can effectively detect species of conservation significance, even when deployed for management purposes. Late detections of rare or hard-to-detect species disrupted saturation at one site, illustrating the sensitivity of accumulation models to detectability. Overall, our results suggest that camera trap surveys targeting specific species can provide valuable additional information on biodiversity, and that by-catch data should be systematically integrated into wildlife monitoring programs. Systematic random designs may offer efficiency advantages for species inventories, although this comparison is observational and confounded by differences in area size and camera density.

KEYWORDS

- Camera traps
- EU habitats directive
- Michaelis-Menten equation
- species accumulation rate

Vom Wildtiermanagement zur Biodiversitätserfassung: Wie sich aus dem Beifang von Kamerafallen auf den Artenreichtum schließen lässt

ZUSAMMENFASSUNG

Im Wildtiermanagement werden Kamerafallen häufig zum Monitoring von Zielarten wie Schalenwild eingesetzt. Die dabei anfallenden umfangreichen Daten zu Nicht-Zielarten werden jedoch nur selten systematisch ausgewertet. In dieser Studie untersuchen wir, ob sich solche managementorientierten Erhebungen mit Kamerafallen nutzen lassen, um Rückschlüsse auf die Biodiversität zu ziehen. Mithilfe von Kamerafallendaten aus vier Untersuchungsgebieten konnten insgesamt 57 Tierarten nachgewiesen werden, darunter 25 Säugetier- und 32 Vogelarten. Der Artenreichtum unterschied sich zwischen den Gebieten, war jedoch nicht primär durch den gesamten Stichprobenumfang bestimmt. Trotz des deutlich höheren Erhebungsaufwands wurden in einer langfristigen, opportunistischen Untersuchung nur geringfügig mehr Arten erfasst als in einer kurzzeitigen Erhebung mit systematisch-zufälligem Studiendesign. Dies deutet auf einen Einfluss der räumlichen Verteilung der Kamerafallen hin; der Vergleich ist jedoch dadurch eingeschränkt, dass sich die Gebiete zugleich in Flächengröße und Kameradichte unterschieden. Die Artenakkumulation wurde mithilfe von Michaelis-Menten-Modellen für jene Taxa analysiert, die sich mit Kamerafallen zuverlässig nachweisen lassen. Systematisch-zufällige Erhebungen erreichten die Sättigung der Artenzahl schneller und zeigten eine raschere Artenakkumulation als das opportunistische Design. Der Anteil der nach der FFH-Richtlinie geschützten Säugetierarten war in allen Untersuchungsgebieten ähnlich hoch. Das zeigt, dass sich Kamerafallen auch im Rahmen managementorientierter Studien eignen, um naturschutzrelevante Arten zuverlässig zu erfassen. Späte Nachweise seltener oder schwer detektierbarer Arten führten in einem Gebiet zu Abweichungen vom erwarteten Sättigungsverlauf und verdeutlichen die Abhängigkeit von Akkumulationsmodellen von der artspezifischen Nachweisbarkeit. Unsere Ergebnisse zeigen insgesamt, dass Erhebungen mit Kamerafallen, die auf Zielarten konzentriert sind, wertvolle zusätzliche Informationen zur Biodiversität liefern können. Wir empfehlen daher, Beifang-Daten systematisch auszuwerten und in bestehende Monitoringprogramme zu integrieren. Um die Artenvielfalt zu erfassen, sind systematisch-zufällige Studien von Vorteil. Dieser Vergleich beruht jedoch nur auf Beobachtungen und wird durch Unterschiede in Flächengröße und Kameradichte zwischen den Gebieten verfälscht.

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INTRODUCTION

Biodiversity monitoring forms the empirical foundation of nature conservation, spatial planning, and ecological research. Reliable information on species occurrence, community composition, and temporal trends is essential for identifying conservation priorities, evaluating wildlife management measures, and detecting ecological change at an early stage [1], [2]. Without systematic monitoring, fundamental questions remain unresolved: Which species are present in a given area? How complete is the observed species inventory? How does biodiversity respond to land use change, habitat fragmentation, or climate-driven shifts? Increasingly, biodiversity-relevant data are also collected incidentally during wildlife management monitoring programs, raising the question of how such data can be used to support broader biodiversity assessments.

Global studies consistently demonstrate that biodiversity is declining at unprecedented rates, affecting not only rare or specialized species but also widespread and formerly common taxa [3]. Against this background, monitoring approaches must be both methodologically robust and scalable, allowing comparisons across sites and time while remaining feasible under practical constraints such as limited personnel, accessibility, and funding.

A wide range of methods has been developed to assess biodiversity of terrestrial vertebrates, particularly mammals and birds. Traditional approaches include direct observations, point counts, transect surveys, capture-mark-recapture techniques, and various forms of live trapping [4]. While these methods have yielded invaluable long-term datasets, they are often labor-intensive and sensitive to observer bias, weather conditions, and species-specific detectability [5]. More recently, technological advances have expanded the methodological toolbox. Environmental DNA (eDNA) sampling enables the detection of multiple taxa from soil, water, or air samples and provides broad taxonomic coverage, although information on abundance, behavior, and temporal dynamics remains limited [6]. For avifauna, passive acoustic monitoring has become a powerful complement to classical surveys, allowing continuous, standardized recording of vocal activity and increasingly automated species identification through machine-learning approaches [7].

For terrestrial mammals, particularly medium- to large-bodied species, camera trapping has emerged as one of the most widely applied non-invasive monitoring techniques [8]. Camera traps (CT) record animals autonomously, day and night, and generate permanent visual records that can be reanalyzed as taxonomic knowledge or analytical tools improve. Also, CTs allow reliable species identification for most medium- and large-bodied mammals and ground-dwelling birds, which is particularly valuable for species that are difficult to identify acoustically or visually during brief field encounters [8], [9], [10]. Camera-based records further enable the analysis of activity patterns, diel and seasonal behavior, and, under certain conditions, relative abundance indices. Because a single deployment records all passing species, camera traps are well suited to multi-species monitoring; detection probability nevertheless varies markedly among species and with survey design, and reliable multi-species comparisons require this variation to be taken into account [11], [12].

Biodiversity can be quantified using various indices and metrics, each capturing different aspects of community structure. Commonly used measures include species richness, Shannon and Simpson indices [13], and functional or phylogenetic diversity metrics. While diversity indices provide valuable summaries, they are inherently dependent on sampling effort (i.e., the sum of active camera-days across all camera locations) and detection probability. Species accumulation curves offer a complementary perspective by explicitly linking observed species richness to sampling effort. They allow an assessment of how rapidly new species are detected and whether sampling approaches a saturation point. Asymptotic models, such as the Michaelis–Menten equation [14], are frequently used to estimate the expected maximum species richness and the effort required to approach it [15], [16]. These models are particularly useful for comparing sampling designs, sites, or monitoring methods under standardized frameworks.

A central question in CT-based monitoring concerns the time required to obtain a sufficiently complete species inventory. While common and highly mobile species are often detected rapidly, rare, cryptic, or wide-ranging species may require substantially longer sampling periods [17]. Very small mammals and species with low ground-level activity are often underrepresented, whereas extremely rare or low-density species, such as large carnivores, may remain undetected despite long deployment times [18]. Understanding species accumulation dynamics is important for interpreting CT results and evaluating sampling completeness. Apparent plateaus may reflect either a genuine reduction in the rate of new species detections or methodological limitations related to detectability and sampling design.

Many CT surveys are conducted within wildlife management programs and are primarily designed to address questions related to specific target species, such as ungulates, due to their influence on forest regeneration and forest stability. In the course of such studies, substantial additional data on non-target species ("by-catch" data) are collected, which can be used to address broader biodiversity-related questions. Such by-catch is increasingly recognized as a valuable resource in its own right and has been used, for example, to characterize community composition, species interactions, and activity patterns [19], [20], to model the occupancy of non-target carnivores across biological and anthropogenic gradients [21], and to infer population trends of threatened species [22]. We aim to evaluate whether such data can be systematically used to infer meaningful patterns of biodiversity and species accumulation of the surveyed areas and provide indications of how camera trap records of non-target species may be used to assess and infer patterns of monitored biodiversity.

Against this background, the present study investigates species accumulation dynamics derived from CT data across multiple study areas with specific wildlife ecological sampling designs and temporal coverage. Specifically, we address the following questions:

1. When does cumulative species richness derived from camera traps approach a plateau, and how does this vary among sites and sampling designs?
2. To what extent can camera traps detect mammal species of conservation concern?
3. Which conservation-relevant bird species are incidentally recorded by camera traps?

By comparing species accumulation curves and selected model outputs across sites, we aim to explore how observed species detection patterns differ between short-term, systematically designed surveys and a long-term, opportunistic deployment, thereby highlighting potential implications for the interpretation of biodiversity data derived from CTs.

Survey area

The study was conducted in four survey areas located in the federal state of Carinthia, southern Austria. The location and spatial arrangement of the four sites, including all

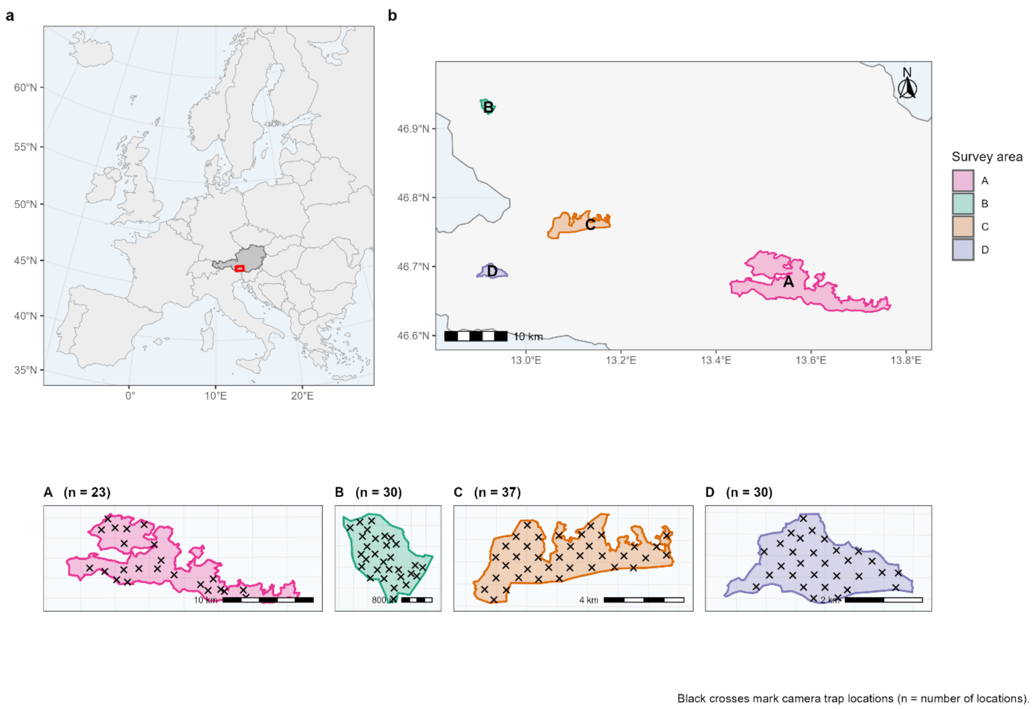

Fig. 1

Figure 1:
The four camera trap survey areas in Upper Carinthia, Austria. (a) Location within Europe (red rectangle). (b) Overview of the sites (A–D) in Carinthia. Insets A–D show close-ups of each site with camera trap locations (black crosses). n denotes the number of camera trap locations per site (120 in total). Coordinates are projected in MGI / Austria GK M31 (EPSG:31258).

Abbildung 1:
Die vier Kamerafallen-Untersuchungsgebiete in Oberkärnten, Österreich. (a) Lage innerhalb Europas (rotes Rechteck). (b) Übersicht der Gebiete (A–D) in Kärnten. Die Ausschnitte A–D zeigen Detailansichten der einzelnen Gebiete mit den Standorten der Kamerafallen (schwarze Kreuze). n bezeichnet die Anzahl der Kamerafallenstandorte pro Gebiet (insgesamt 120). Die Koordinaten sind in MGI / Austria GK M31 (EPSG:31258) projiziert.

CT placement locations, are shown in the study area map (Figure 1). Together, the sites span three floristic regions, reflecting pronounced gradients in climate, topography, and vegetation (Table 1). The combined elevational range of the study areas extends from approximately 600 to 2,200 m a.s.l., with this full gradient being covered primarily by site A, which represents by far the largest spatial extent among the four areas.

Tab. 1

Survey	Elevation Range (m a.s.l.)	Area (km^2)	Floristic Regions [23]	CT Locations	CT/km^2	Years of Deploy-ment	Active Camera-Days	Deployment Type
A	600-2,200	95.0	3.3 6.1	23	0.2	2015-2020	21,520	Wildlife trails, Baited clearings (salt)
B	1,000-1,700	2.9	1.2	25	8.6	2023-2024	2,462	Systematic-random
C	600-1,850	20.5	3.3	37	1.8	2023-2024	4,046	Systematic-random
D	900-1,600	5.7	6.1	30	5.3	2023-2024	3,282	Systematic-random

Table 1:
Overview of the four camera trap survey areas, including elevation range, spatial extent, assigned floristic regions after Kilian et al. [23], deployment period, number of camera trap locations, total active camera-days, and deployment strategy.

Tabelle 1:
Übersicht der vier Kamerafallen-Untersuchungsgebiete mit Höhenlage, räumlicher Ausdehnung, zugeordneten Wuchsgebieten nach Kilian et al. [23], Erfassungszeitraum, Anzahl der Kamerafallenstandorte, Gesamtzahl der aktiven Kamerafallentage und Ausbringungsstrategie.

According to the forest ecological regionalization of Austria by Kilian et al. [23], the study areas are situated within floristic regions 1.2 (Subcontinental Inner Alps – western part), 3.3 (Southern Intermediate Alps), and 6.1 (Southern Alpine fringe ranges). The first region is characterized by a subcontinental inner-alpine climate with relatively low annual precipitation compared to the northern Alpine margin, pronounced seasonal temperature amplitudes, and a summer precipitation maximum [23]. Vegetation is dominated by montane to subalpine coniferous forests, primarily Norway spruce (*Picea abies*), often accompanied by larch (*Larix decidua*) and, at lower elevations, mixed spruce-fir-beech forests on more mesic sites. Floristic region 3.3 (Southern Intermediate Alps) exhibits a transitional climate influenced by both Alpine and sub-Mediterranean conditions, with generally higher precipitation and milder winters than the inner-alpine regions. Vegetation includes montane mixed forests dominated by European beech (*Fagus sylvatica*), silver fir (*Abies alba*), and Norway spruce, with a diverse understory and locally extensive broadleaf components, particularly on nutrient-rich substrates. Floristic region 6.1, representing the Southern Alpine fringe ranges, is characterized by comparatively warm and humid climatic conditions with a strong influence from southern air masses. Annual precipitation is high, and snow cover duration is shorter than in inner-alpine regions. Vegetation is dominated by species-rich montane beech forests, often transitioning into mixed beech-fir-spruce forests at higher elevations, while thermophilous broadleaf forests occur locally at lower elevations.

The ungulate community across all study areas is dominated by red deer (*Cervus elaphus*), roe deer (*Capreolus capreolus*), and chamois (*Rupicapra rupicapra*), while wild boar (*Sus scrofa*) occurs only sporadically and at low densities. Large carnivores expected to occur within the study region include the grey wolf (*Canis lupus*), brown bear (*Ursus arctos*), and Eurasian lynx (*Lynx lynx*), all of which are subject to ongoing recolonization dynamics in the Eastern Alps.

METHODS

Study design and data origin

The four study sites were surveyed within the framework of commissioned projects aimed at estimating ungulate density, as well as their social structure and activity patterns, using CTs. Consequently, the CT deployment was primarily optimized for the detection of large terrestrial mammals. All additional species recorded by the cameras represent incidental detections—or by-catch—that were subsequently used to address complementary research questions.

Camera trap equipment and settings

We used multiple camera models, including Bushnell Core DS (Bushnell Outdoor Products, Hyde Park, UT, USA) and Browning Patriot (Browning International S.A., Morgan, UT, USA). CTs were mounted at a height of 50–80 cm above ground level on suitable trees and were preferentially oriented northward to minimize direct sunlight exposure and false triggers. All cameras were programmed to capture eight images per trigger event at a resolution of 4 megapixels, with no delay between consecutive trigger events. This configuration allowed for continuous observation of animals within the detection zone and provided a high temporal resolution of animal movements. Each image was automatically annotated with date, time, temperature, and air pressure at the moment of triggering. All cameras were set to the highest sensitivity level to maximize detection probability. The flash mode was set to “Power Save”. Image data were stored on 32-GB SD cards. Battery levels were checked during each SD card exchange and batteries were replaced when necessary. To reduce false triggers, care was taken to avoid placing cameras where the motion sensor could be activated by dense or tall vegetation moving within the field of view.

Camera trap placement

Study site A

In study site A, CTs were deployed using a non-random, management-oriented approach aimed at increasing the likelihood of detecting ungulates (see Table 1). Camera locations included game trails, salt licks, meadows, and areas adjacent to browsing test sites. Over the course of the long-term monitoring period, camera placement was not static: a subset of locations remained active for extended periods, while others were relocated periodically or deployed only once for a limited duration of several weeks to months. Deployment duration varied markedly among camera locations, ranging from 113 to 1,828 active camera-days (median 960): seven locations were active for less than one year, whereas nine accumulated images during three to five years of operation. This highly uneven per-location effort strongly influenced the shape of the species accumulation curve for site A. As a result, sampling effort was distributed unevenly across space and time, reflecting an opportunistic deployment strategy rather than a systematically random design. Consequently, data from site A are not directly comparable to those from the short-term surveys in terms of standardized sampling effort but provide complementary, long-term insights derived from repeated and flexible camera deployments.

Study sites B-D

In study sites B-D, cameras were deployed using a grid-based systematic-random design commonly applied in Random Encounter Model (REM) studies [24]. A regular grid was overlaid on each study area, and CT locations were defined at the grid intersection points. Minor spatial adjustments were permitted where grid points fell on roads, paths, or agricultural land. In contrast to site A, game trails or movement corridors were not explicitly visited, but they weren't specifically avoided either.

Image processing and data management

After retrieval of the SD cards, image files were processed manually or by using MegaDetector [25] and Timelapse [26] software to remove empty images. Empty images were defined as photographs without animal presence, most commonly triggered by vegetation moving or warmed by sunlight within the camera's detection range.

The filtered image sets were subsequently uploaded to Camelot [27] (site A) or to the Agouti [28] online platform (sites B-D), where images were automatically grouped into independent detection events to facilitate further classification and analysis.

Taxonomic scope and modelling approach

The Michaelis–Menten model was fitted to taxa for which CTs provide reliable detections and are suitable for asymptotic species accumulation modelling. These included:

- insectivores
- rodents
- carnivores
- ungulates
- lagomorphs
- ground-dwelling birds, specifically all grouse species and woodcock (*Scolopax rusticola*), as well as common songbird species, which were detected in all four areas.

All bat species and other non-terrestrial bird species were excluded from the analysis. Although CTs recorded a substantial number of additional bird species—such as finches, tits and other woodpeckers, which may occasionally forage on the ground—their detection by CTs is considered opportunistic and methodologically unsuitable for saturation-based modelling. Consequently, these species were excluded to ensure biological interpretability and methodological consistency of the fitted models.

RESULTS

Across all four study sites, camera trapping recorded a total of 57 species, of which 32 were birds and 25 were mammals (Table 2). Species richness differed among sites. The long-term study site A yielded the highest number of detected species (n = 42). The short-term study site B showed comparable richness (n = 40), whereas the remaining two sites supported fewer species (site C: n = 27; site D: n = 28).

Tab. 2

Nr	Taxon	Species	Scientific Name	Survey Area				Annex
				A	B	C	D	
1	insectivores	brown-breasted hedgehog	*Erinaceus europaeus*				x	
2	bats	bats	Chiroptera	x		x		II;IV
3		edible dormouse	*Glis glis*	x		x	x	
4		**marmot**	*Marmota marmota*		1			
5	rodents	squirrel	*Sciurus vulgaris*	x	x	x	x	
6		**forest dormouse**	*Dryomys nitedula*		3			IV
7		wood mouse	*Apodemus* sp.	x	x	x		
8		badger	*Meles meles*	128	6	2	5	
9		**brown bear**	*Ursus arctos*	1				II;IV
10		**golden jackal**	*Canis aureus*		1			V
		marten	*Martes martes/foina*	127	131	95	84	
11	carnivores	**pine marten**	*Martes martes*	24			2	V
12		**polecat**	*Mustela putorius*			1		V
13		red fox	*Vulpes vulpes*	1,288	457	227	88	
14		stone marten	*Martes foina*	2	6			
15		weasel	*Mustela nivalis/erminea*			1	2	
16		**wolf**	*Canis lupus*		2		2	V
17		**chamois**	*Rupicapra rupicapra*	6,600	527	56	11	V
18		mouflon	*Ovis gmelini*	1				
19	ungulates	red deer	*Cervus elaphus*	59,903	624	1,370	313	
20		roe deer	*Capreolus capreolus*	9,922	406	1,376	1,636	
21		wild boar	*Sus scrofa*	2				
22	lagomorphs	European hare	*Lepus europaeus*	2,410	10	8	9	
23		**mountain hare**	*Lepus timidus*	28	11	12	4	V

Table 2:
Species detected with camera traps in four survey areas, listed alphabetically by taxonomic group. Bold font indicates species listed under Annex II, IV or V of the EU Habitats Directive and Annex II of the Birds Directive respectively. Numbers indicate the total number of detections, whereas "x" indicates only presence, without exact counts.

Tabelle 2:
Mit Kamerafallen nachgewiesene Arten in vier Untersuchungsgebieten, alphabetisch nach taxonomischer Gruppe geordnet. Fett gedruckte Arten, sind in Anhang II, IV oder V der FFH-Richtlinie bzw. in Anhang II der Vogelschutzrichtlinie gelistet. Die Zahlen geben die Gesamtzahl der Nachweise an, während „x" lediglich das Vorkommen ohne genaue Zählung angibt.

24		blackbird	*Turdus merula*	x	x	x	x	
25		black woodpecker	*Dryocopus martius*	37	3		2	I
26		blue tit	*Cyanistes caeruleus*	x				
27		bullfinch	*Pyrrhula pyrrhula*		x			
28		buzzard	*Buteo buteo*	165	3			
29		**capercaillie**	*Tetrao urogallus*	108		2	18	I;II
30		chaffinch	*Fringilla coelebs*	x	x	x		
31		chiffchaff	*Phylloscopus collybita*		x			
32		crested tit	*Lophophanes cris-tatus*	x	x	x		
33		dunnock	*Prunella modularis*		x			
34		**Eurasian jay**	*Garrulus glandarius*	189	18	23	14	II
35		Eurasian sparrowhawk	*Accipiter nisus*		1			
36		goshawk	*Accipiter gentilis*	25		1		
37		boreal owl	*Aegolius funereus*		1			I
38		great tit	*Parus major*	x	x		x	
39		great-spotted woodpecker	*Dendrocopos major*	7	4	3	2	
40	birds	green woodpecker	*Picus viridis*		2			
41		grey-headed woodpecker	*Picus canus*		1			I
42		**hazel grouse**	*Tetrastes bonasia*	1		1	3	I;II
43		long-tailed tit	*Aegithalos caudatus*	x				
44		**mistle thrush**	*Turdus viscivorus*	x	x	x	x	II
45		nutcracker	*Nucifraga caryocatactes*	x	x	x	x	
46		nuthatch	*Sitta europaea*	x	x			
47		raven	*Corvus corax*	1	2			
48		**redwing**	*Turdus iliacus*		x			II
49		robin	*Erithacus rubecula*	x	x	x	x	
50		**rock partridge**	*Alectoris graeca*		1		3	I;II
51		**song thrush**	*Turdus philomelos*	x	x	x	x	II
52		tawny owl	*Strix aluco*	32	2		1	
53		whinchat	*Saxicola rubetra*	x				
54		**wood pigeon**	*Columba palumbus*	4,898	x	x	x	II
55		**fieldfare**	*Turdus pilaris*	x				II
56		**woodcock**	*Scolopax rusticola*	5				II
57		wren	*Troglodytes troglodytes*	x				
	N species	57		42	40	27	28	
	N species FFH Annex II			2	1	1	1	
	N species FFH Annex IV			2	2	1	1	
	N species FFH Annex V			3	3	3	3	
	N species FFH Annex II, IV or V			5	5	4	4	
	Proportion of FFH-listed species by total number of species			12%	13%	15%	14%	

Mammals

The 25 mammalian species detected—a selection of which is shown in Figure 2—comprised one insectivore, the brown-breasted hedgehog (*Erinaceus europaeus*), at least one bat species (Order: Chiroptera), five rodent species, ten carnivores, five ungulates, and two lagomorphs. Bat detections occurred at two study sites and were sporadic, but without species-level identification.

Nine mammal species were detected at all four study sites, indicating widespread occurrence across the region. These included squirrel (*Sciurus vulgaris*), badger (*Meles meles*), martens (*Martes martes* and *Martes foina*), red fox (*Vulpes vulpes*), as well as European hare (*Lepus europaeus*) and mountain hare (*Lepus timidus*), in addition to red deer, roe deer, and chamois.

Nine of the recorded mammal species are listed under the EU Habitats Directive (FFH Directive) in one or more annexes. Three species are included in Annex II, four in Annex IV, and four in Annex V. Among these, the forest dormouse (*Dryomys nitedula*) represents one of the seven FFH-listed rodent species known from Austria. The mountain hare was the only lagomorph species found that is listed under the Directive.

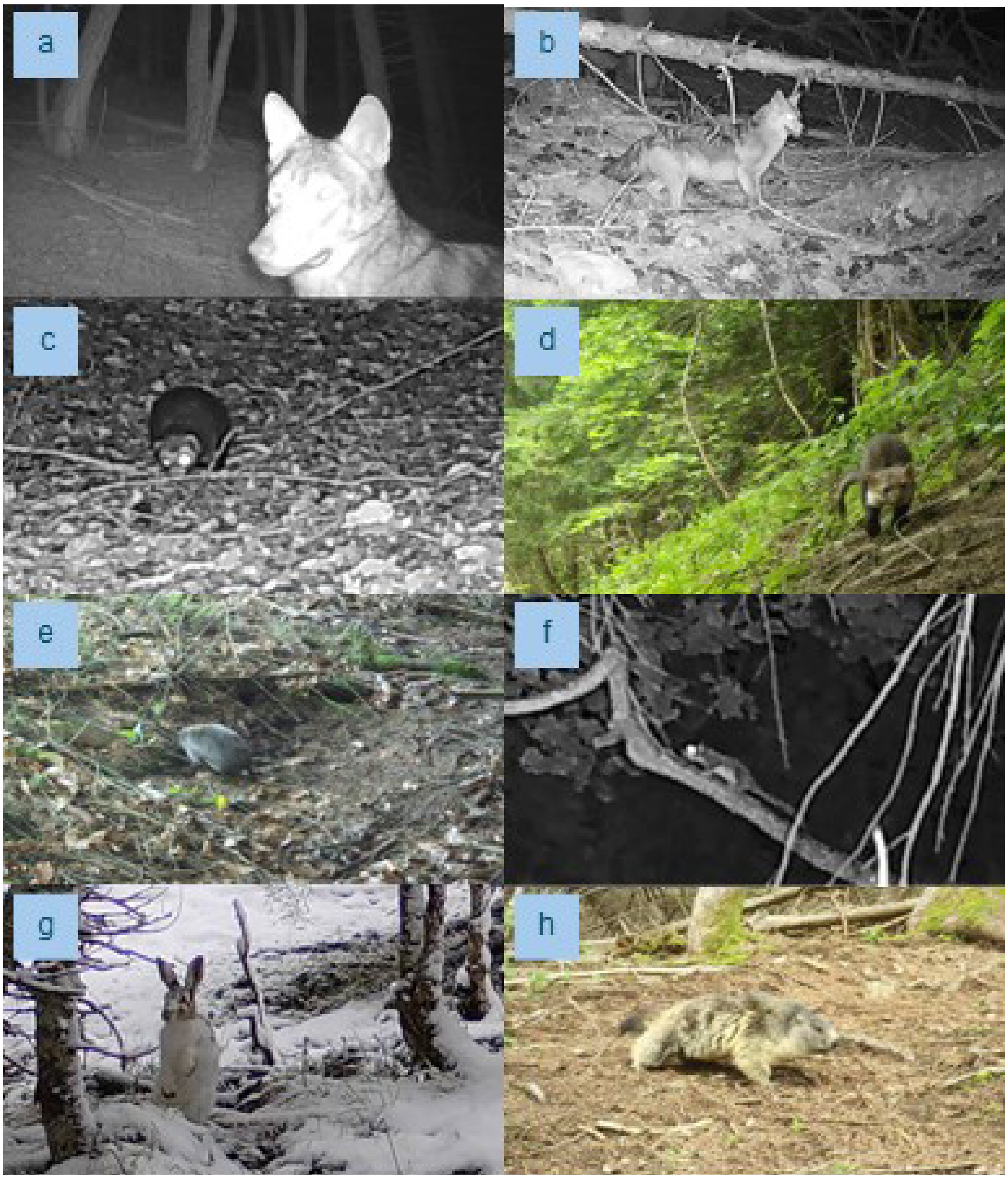

Fig. 2

Figure 2: Selection of mammal species captured with camera traps showing a) wolf (*Canis lupus*), b) golden jackal (*Canis aureus*), c) polecat (*Mustela putorius*), d) pine marten (*Martes martes*), e) brown-breasted hedgehog (*Erinaceus europaeus*), f) forest dormouse (*Dryomys nitedula*), g) mountain hare (*Lepus timidus*) and h) marmot (*Marmota marmota*).

Abbildung 2: *Auswahl der mit Kamerafallen erfassten Säugetierarten: a) Wolf (Canis lupus), b) Goldschakal (Canis aureus), c) Iltis (Mustela putorius), d) Baummarder (Martes martes), e) Braunbrustigel (Erinaceus europaeus), f) Baumschläfer (Dryomys nitedula), g) Schneehase (Lepus timidus) und h) Murmeltier (Marmota marmota).*

Five of the recorded carnivores are listed under the EU Habitats Directive: brown bear, wolf, golden jackal (*Canis aureus*), pine marten (*Martes martes*), and polecat (*Mustela putorius*), representing five of the eight FFH-listed carnivores occurring in Austria. Several of these were recorded only as isolated events: brown bear (Annex II/IV) was detected a single time at site A, golden jackal (Annex V) once at site B, and polecat (Annex V) once at site C, while wolf (Annex V) was recorded at two sites (twice each at site B and site D).

Notably, when expressed relative to total species richness per site, the proportion of mammal species listed in FFH Annexes II, IV, or V remained within a narrow band of 12-15% across all four study areas (A: 12%, B: 13%, C: 15%, D: 14%). This consistency is a key result of our study: despite the areas differing more than thirty-fold in size (2.9-95 km²) and in sampling design, effort, and camera density, the relative representation of conservation-relevant mammals was remarkably stable. This indicates that the conservation-relevant signal carried by CT by-catch is robust to substantial differences in survey design and supports its value as an additional output of focal species monitoring.

Birds

In total, 32 bird species were detected by CTs (a selection is shown in Figure 3). Of these, 16 species are listed under the EU Birds Directive. Six of the recorded bird species

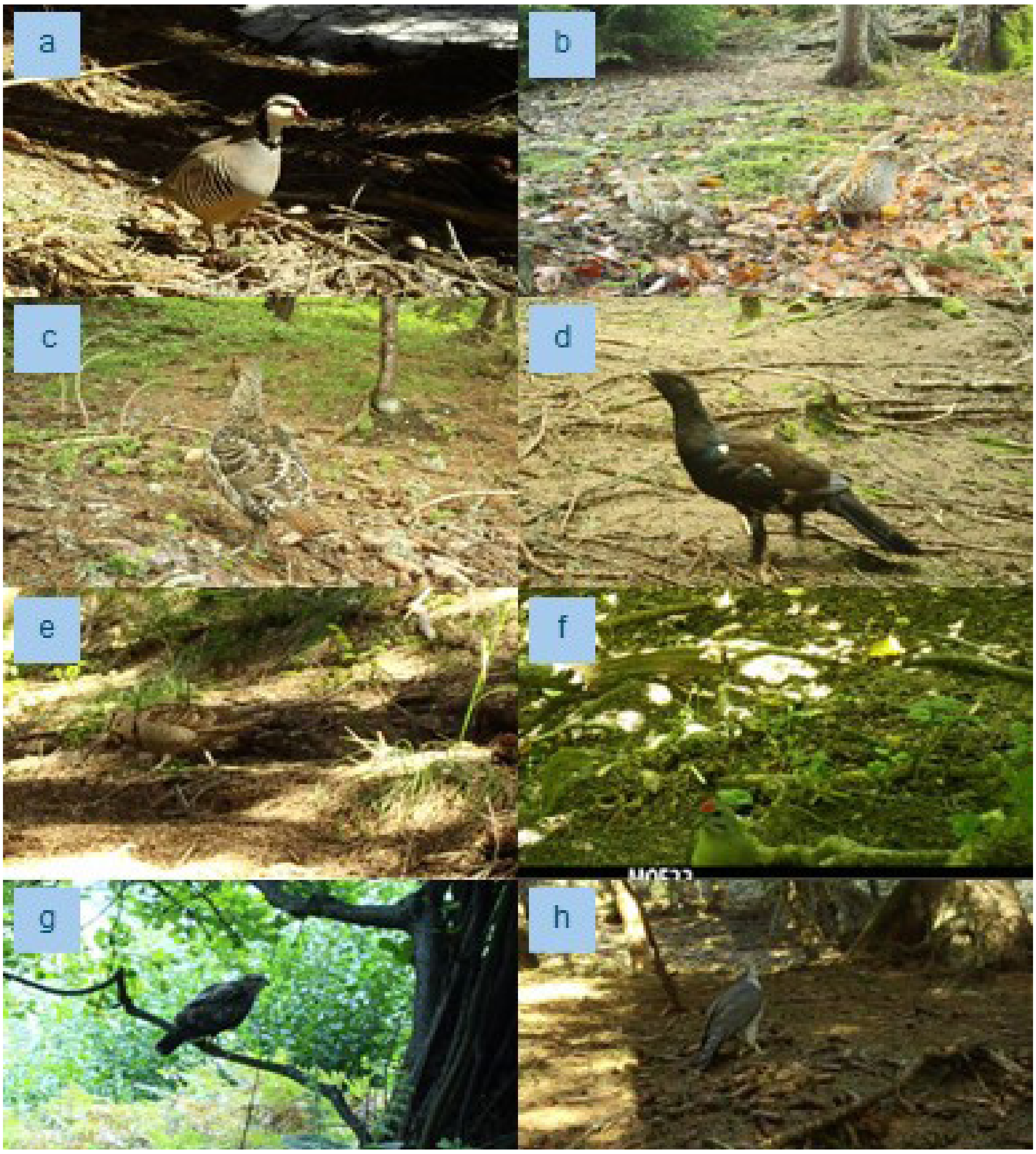

Fig. 3

Figure 3: Selection of bird species captured with camera traps, showing a) rock partridge (*Alectoris graeca*), b) hazel grouse male and female (*Tetrastes bonasia*), c) female capercaillie (*Tetrao urogallus*), d) male capercaillie (*Tetrao urogallus*), e) woodcock (*Scolopax rusticola*), f) grey-headed woodpecker (*Picus canus*), g) buzzard (*Buteo buteo*) and h) goshawk (*Accipiter gentilis*).

Abbildung 3: *Auswahl der mit Kamerafallen erfassten Vogelarten: a) Steinhuhn (Alectoris graeca), b) Haselhuhn, Hahn und Henne (Tetrastes bonasia), c) Auerhenne (Tetrao urogallus), d) Auerhahn (Tetrao urogallus), e) Waldschnepfe (Scolopax rusticola), f) Grauspecht (Picus canus), g) Mäusebussard (Buteo buteo) und h) Habicht (Accipiter gentilis).*

(capercaillie, *Tetrao urogallus*; hazel grouse, *Tetrastes bonasia*; rock partridge, *Alectoris graeca*; boreal owl, *Aegolius funereus*; grey-headed woodpecker, *Picus canus*; black woodpecker, *Dryocopus martius*) are listed in Annex I of the EU Birds Directive and therefore require special conservation measures in Austria. Ten of the recorded bird species are listed in Annex II of the EU Birds Directive.

As with the conservation-relevant mammals, several of these Annex I species were recorded only incidentally and in very low numbers: rock partridge was detected once at site B and three times at site D, grey-headed woodpecker and boreal owl once each at site B, and hazel grouse at three sites in single-digit counts. In contrast, capercaillie and black woodpecker were recorded repeatedly and across multiple sites. That scarce, ground-associated Annex I species appeared at all surveys designed for ungulates further underlines the conservation value of systematically evaluating CT by-catch.

Nocturnal raptors were represented by the boreal owl and the tawny owl (*Strix aluco*), while diurnal raptors included the common buzzard (*Buteo buteo*), Eurasian sparrowhawk (*Accipiter nisus*), and northern goshawk (*Accipiter gentilis*).

Species Accumulation

Species accumulation was modelled using a Michaelis–Menten equation [14], where V_{max} represents the expected asymptotic species richness and K indicates the sampling effort (in camera-days) required to reach half of V_{max}. Lower K values therefore reflect a faster accumulation of species. In addition, the sampling effort T when V_{max} reached 95 % (T V_{max}95%) was used as a standardized measure of the sampling effort required to approach species saturation.

Clear differences were observed between the long-term, opportunistic study site (A) and the short-term, systematically random surveys of sites B–D (Table 3). The long-term site A showed a high K value (2,514.8) and required substantially more sampling effort to approach saturation, as reflected by the markedly delayed T V_{max}95% (47,781.8). In contrast, all three systematically random sites exhibited much lower K values between 221 and 255 and reached 95% of the estimated V_{max} considerably earlier with T V_{max}95% between 4,202 and 4,843 camera-days.

Table 3: Parameters of Michaelis–Menten species accumulation models for the four study sites, including the estimated asymptotic species richness (V_{max}), the sampling effort required to reach half of V_{max} (K), the empirically observed maximum number of species, and the sampling effort at which 95% of V_{max} was reached (T V_{max}95%). Results are shown for the long-term, opportunistic deployment (site A) and the short-term, systematically random surveys (sites B–D).

Tabelle 3: *Parameter der Michaelis-Menten-Artenakkumulationsmodelle für die vier Untersuchungsgebiete, einschließlich des geschätzten asymptotischen Artenreichtums (V_{max}), des zum Erreichen der Hälfte von V_{max} erforderlichen Erfassungsaufwands (K), der empirisch beobachteten maximalen Artenzahl sowie des Erfassungsaufwands, bei dem 95 % von V_{max} erreicht wurden (T V_{max}95%). Die Ergebnisse sind für die langfristige, opportunistische Ausbringung (Gebiet A) und die kurzfristigen, systematisch-randomisierten Erhebungen (Gebiete B–D) dargestellt.*

Tab. 2

Site	Sampling design	V_{max} (± SE)	K (± SE)	V_{max} empirical	T first V_{max} empirical	T V_{max}95%
A	Long-term (multi-year)	25.2 ± 0.3	2,514.8 ± 114.8	24	19,544.0	47,781.8
B	4 × 1 month	23.4 ± 0.8	222.2 ± 41.7	23	2,287.2	4,221.1
C	4 × 1 month	19.3 ± 0.6	254.9 ± 48.7	21	4,045.8	4,843.3
D	4 × 1 month	25.1 ± 0.3	221.2 ± 16.9	24	2,757.0	4,202.7

Estimated V_{max} values were generally close to the empirically observed species richness at sites A, B, and D (Figure 4). Site C deviated from this pattern: late detections of song thrush (*Turdus philomelos*), edible dormouse (*Glis glis*), and capercaillie produced a step-like increase in cumulative richness towards the end of the sampling period, which weakened the Michaelis–Menten fit and even yielded an estimated asymptote below the empirically observed maximum. This case highlights a key limitation of asymptotic accumulation models: when rare or seasonally detectable species are recorded late, the curve fails to saturate and the model becomes unsuitable, irrespective of survey design.

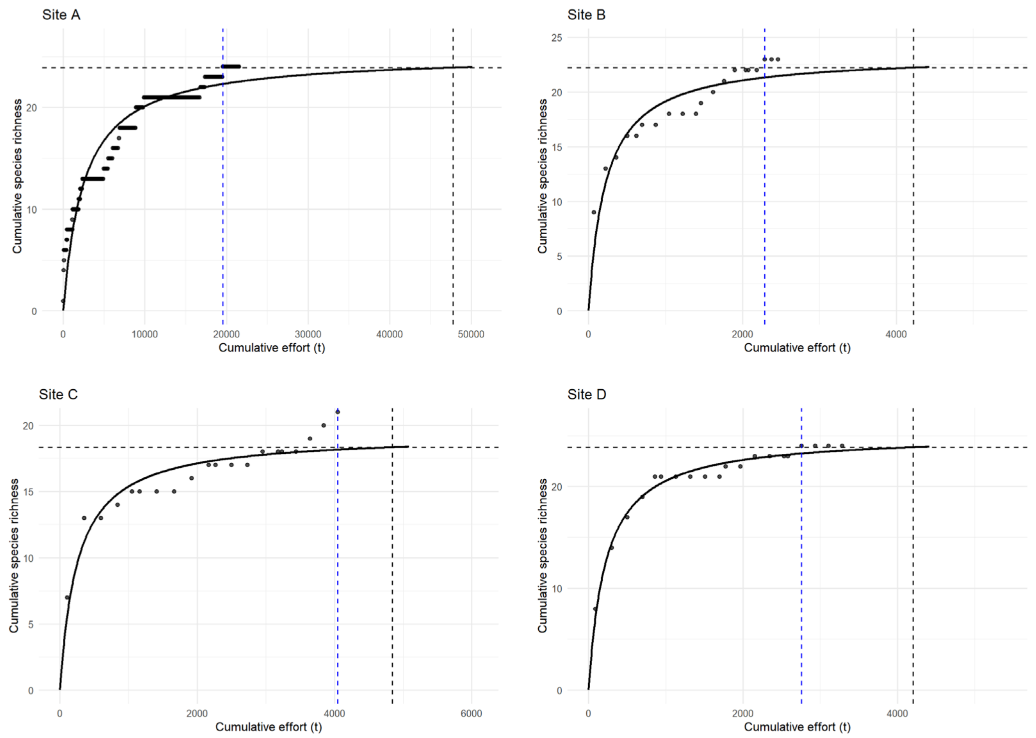

Fig. 4

Figure 4: Michaelis–Menten species accumulation curves for the four study sites. Points represent empirical cumulative species richness as a function of cumulative sampling effort (t), and the solid line shows the fitted Michaelis–Menten model. The horizontal dashed line indicates the modelled asymptotic species richness (V_{max}) derived from the Michaelis–Menten function, not the empirically observed maximum. The blue vertical dashed line marks the sampling effort at which the empirical maximum species richness was first reached. The black vertical dashed line denotes the sampling effort required to reach 95% of the modelled V_{max} ($T\,V_{max}95\%$), providing a standardized measure of the speed at which species saturation is approached.

Abbildung 4: *Michaelis-Menten-Artenakkumulationskurven für die vier Untersuchungsgebiete. Die Punkte stellen den empirischen kumulativen Artenreichtum als Funktion des kumulativen Erfassungsaufwands (t) dar; die durchgezogene Linie zeigt das angepasste Michaelis-Menten-Modell. Die horizontale gestrichelte Linie kennzeichnet den modellierten asymptotischen Artenreichtum (V_{max}) aus der Michaelis-Menten-Funktion, nicht das empirisch beobachtete Maximum. Die blaue vertikale gestrichelte Linie markiert den Erfassungsaufwand, bei dem die empirische maximale Artenzahl erstmals erreicht wurde. Die schwarze vertikale gestrichelte Linie kennzeichnet den zum Erreichen von 95 % des modellierten V_{max} erforderlichen Erfassungsaufwand ($T\,V_{max}95\%$) und liefert damit ein standardisiertes Maß für die Geschwindigkeit, mit der sich die Artensättigung annähert.*

DISCUSSION

This study shows that CT data originally collected within wildlife management programs can be effectively used to extract meaningful information on broader biodiversity patterns. Across the four survey sites, camera trapping enabled the detection of a diverse range of terrestrial vertebrates, including mammals from six orders as well as birds, with a total of 57 species recorded. This supports the general suitability of CTs for multi-taxon biodiversity assessments in heterogeneous landscapes. However, species detection was not primarily driven by total sampling effort. Instead, differences in study design appeared to be a key factor shaping species accumulation patterns.

Despite a substantially longer deployment period in site A, which followed an opportunistic and non-random placement strategy, only marginally more species were detected compared to site B, where cameras were placed following a systematic random design. This shows that longer sampling does not necessarily lead to many additional species when camera placement is uneven, and that spatial coverage plays a key role in species detection [9], [17].

However, site A differed from sites B–D not only in placement strategy but simultaneously in spatial extent (95 km² versus 2.9–20.5 km²), camera trap density (approximately 0.24 versus 1.8–8.6 cameras km^{-2}) and habitat heterogeneity. These factors are known to influence species detection independent of placement strategy [12], [29], and our four datasets—originating from independently commissioned projects—do not allow them to be disentangled. The comparison should therefore be regarded as observational rather than as a controlled test of sampling design. Notably, cameras in site A were placed at game trails and baited salt licks, which generally increase per-camera detection rates; the slower species accumulation at this larger site despite such placement is consistent with area size and spatial coverage, rather than placement strategy alone, limiting inventory completeness.

The proportion of mammal species listed under the EU Habitats Directive (FFH), excluding bats, remained within a narrow band of 12-15% across all four study sites. This stability is striking given that the areas differed more than thirty-fold in size (2.9–95 km²) and in sampling design, effort, and camera trap density. It suggests that the conservation-relevant signal carried by camera trap by-catch is largely robust to these design differences, and that even surveys optimized for ungulates capture a representative cross-section of FFH-listed mammals [30, 31]. This robustness is, in our view, the most transferable result of the study: it is precisely what makes by-catch a worthwhile additional output of focal species monitoring, rather than a byproduct to be discarded [30].

For certain species, camera trapping appears particularly well suited. Medium- to large-bodied terrestrial mammals such as mountain hare and chamois were detected consistently, supporting the use of CTs for their monitoring. Of the two FFH-listed ungulate species considered in this study, only chamois was detected. The absence of Alpine ibex (*Capra ibex*) can be explained by the fact that all study sites lie outside the species' natural distribution range. In contrast, species that are primarily nocturnal and morphologically similar, such as polecat and martens, pose identification challenges when infrared cameras are used. For these taxa, white-flash cameras can substantially improve species-level identification and should be preferred when these species are focal targets.

Although bats were detected at two study sites, CT images do not allow reliable species-level identification. Most bat species can only be identified based on species-specific echolocation calls obtained through acoustic monitoring or, in some cases, through morphological examination of captured individuals, including body measurements and diagnostic physical characteristics. Given that more than 20 bat species occur in Carinthia, the records obtained in this study likely represent multiple species rather than a single taxon.

Large carnivores such as brown bear and wolf were detected only sporadically, reflecting both their low densities and wide-ranging behavior. These records illustrate that even rare, wide-ranging, or low-density species of high conservation interest may be detected incidentally in management-oriented CT surveys. However, such sporadic detections should not be interpreted as evidence of established occurrence or population status. During the study period, the protection status of the wolf under the EU Habitats Directive was downgraded from Annex IV to Annex V, highlighting the importance of reliable monitoring data for informing conservation and management decisions. Incidental detections, as observed here, should therefore be interpreted cautiously and cannot replace dedicated monitoring schemes. Targeted, non-random camera placement, often combined with baits, remains necessary for reliable monitoring of these species [32], [33], [34]. For wolf and golden jackal, complementary approaches such as acoustic monitoring and genetic analyses of scat may provide more robust information, as the latter is already common practice for Eurasian otter [32], [35].

Species that are strongly bound to aquatic habitats, such as beaver, are unlikely to be detected consistently in terrestrial CT settings, such as ours. Nevertheless, CTs placed strategically at riverbanks or crossing points can still contribute valuable presence data [36]. Finally, small rodents were largely underrepresented, which is expected given their body size and movement patterns. Their detection would require specialized setups, such as ground-level cameras integrated into non-lethal box traps [37], underscoring that CTs alone cannot comprehensively sample all components of terrestrial vertebrate communities.

Species richness represents the total number of species present, whereas species accumulation describes how this richness is revealed progressively as sampling effort increases. Species accumulation patterns were analyzed using Michaelis–Menten models fitted to a filtered set of species, as described in the Methods section. Accordingly, all accumulation parameters reflect patterns within this detectable subset of the vertebrate community. Across study sites, systematically random camera placements consistently reached 95% of the estimated asymptotic species richness more rapidly than the long-term opportunistic deployment. This indicates that spatially structured camera placement promotes faster accumulation of species, even when overall sampling duration is limited.

The markedly higher K value estimated for site A further underlines this pattern. In the context of the Michaelis–Menten model, a higher K value reflects a slower initial accumulation of species, suggesting that many species required extended sampling time before detection. In contrast, consistently lower K values at the systematically random sites point to more efficient sampling of the community, with a larger fraction of species detected early in the survey period. Together, these results provide strong empirical support for systematic random camera placement as an effective strategy for biodiversity inventories. These findings closely align with findings of Si et al. [17] who showed that species detection in camera trap studies depends more strongly on spatial coverage and camera rotation than on prolonged deployment at a limited number of sites.

Site C deviated from the expected saturating accumulation pattern despite systematic random placement and high spatial replication. Late detections of several species (namely song thrush, edible dormouse and capercaillie) produced a step-like increase late in the sampling period, which substantially reduced the fit of the Michaelis–Menten model and even resulted in an estimated asymptote below the empirical maximum. Such patterns can arise when detectability is strongly time-varying (e.g., seasonal shifts, snow cover), when effort is temporally uneven among camera locations, or when species are rare.

A further important consideration is that species detection depends not only on deployment duration and placement strategy, but also on technical and methodological factors. Camera characteristics such as sensor sensitivity, trigger speed, field of view, camera angle, and mounting height can substantially influence detection probability and therefore affect observed species richness and accumulation dynamics [38]. Small differences in camera positioning may particularly affect the detectability of small-bodied species or species with specific movement behavior. Consequently, variation in technical setup among surveys may partly contribute to differences in species accumulation patterns observed between sites.

In addition, estimates of species saturation are influenced by the analytical approach used to model accumulation curves. In the present study, species accumulation was analyzed using Michaelis–Menten models, which assume an asymptotic saturation process. However, alternative modelling approaches may produce different estimates of saturation thresholds and sampling efficiency. For example, Beukes et al. [39] applied a logistic growth model to estimate species accumulation dynamics in CT surveys. Such methodological differences should be considered when comparing results among studies, as estimates of saturation are partly model-dependent.

Methodological limitations and future research directions

Several methodological limitations of this study should be acknowledged. As in most long-term CT studies, a proportion of cameras failed prematurely due to technical issues such as battery depletion, limited storage capacity, malfunction, or theft, resulting in unavoidable data loss. To compensate for such losses, we recommend planning for an additional 10–20% of camera units beyond the intended deployment. Differences in camera models, placement heights, and detection settings may also have influenced detection probabilities among sites. Moreover, our datasets originate from wildlife management surveys explicitly designed to monitor ungulates, which constrains the degree to which camera placement and settings could be optimized for broader biodiversity assessment. This represents an inherent limitation of the study and limits the extent to which alternative survey designs can be recommended. Finally, the opportunistic nature of some deployments introduces spatial bias that complicates direct comparisons of species accumulation parameters. Future studies should therefore aim for greater standardization of camera settings and consider stratified placement approaches to ensure a more balanced coverage of different habitat types, where management objectives allow.

Practical implications for wildlife management and conservation

From an applied perspective, our results provide clear guidance for wildlife managers and conservation practitioners. CT surveys designed to monitor one or more focal species, such as ungulates, can simultaneously yield valuable information on broader biodiversity. Failing to systematically analyze and integrate this ancillary information would represent a substantial loss of ecological data. We therefore recommend that the evaluation of non-target species detections be standardized and routinely incorporated into wildlife monitoring programs.

The incidental detection of several bird species listed under Annex II of the EU Birds Directive further illustrates that camera trap surveys conducted for wildlife management purposes can also provide relevant information on game bird species of conservation and management interest.

For broad-scale biodiversity inventories and early detection of community composition, systematic random CT designs are recommended, as they maximize spatial coverage and accelerate species detection. Opportunistic long-term deployments may still be valuable for documenting rare events or behavioral observations, but they are less efficient for estimating species richness.

Camera trapping can be confidently recommended for monitoring medium- and large-bodied terrestrial mammals, including several conservation-relevant species in habitats of very different sizes. However, species-specific adaptations in study design and complementary methods remain essential when monitoring elusive carnivores, aquatic mammals, or small rodents. Overall, camera trapping represents a powerful and flexible tool, but its effectiveness depends critically on thoughtful study design and clearly defined monitoring objectives.

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ABOUT THE AUTHORS

Stephanie Wohlfahrt
BIOLOGIK –
Dr. Stephanie Wohlfahrt
9300 Frauenstein
Austria
E-Mail: wohlfahrt@biologik.at

Horst Leitner
Büro für Wildökologie und Forstwirtschaft
DI Horst Leitner
9020 Klagenfurt, Austria

BACK TO CONTENT

Short Articles

Implementing GPS logger data for visitor monitoring in the Karawanken–Karavanke UNESCO Global Geopark

Sabrina Muscolino, Lilia Schmalzl, Julian Greiler

KEYWORDS
- GPS tracking
- Ecotourism
- Human-Nature Coexistence
- CUAS

ABSTRACT

Human-Nature coexistence is an increasingly important component in the sustainable management of conservation areas. Pioneering conservation approaches are focused on integrating these two aspects rather than creating a strict separation. Disruptions to the balance between humans and nature can affect both natural resource conservation and the tourist experience. To avoid this, resource, infrastructure, and tourism flow management plans are needed. The HUMANITA project aims to develop innovative solutions to monitor tourism and its impact on the environment within selected conservation areas in Central Europe. It includes several methods to estimate tourism numbers, hotspots, and activities. We distributed 69 GPS loggers in the Karawanken–Karavanke UNESCO Global Geopark and created visitor density and intensity maps. This study demonstrates that GPS logger tools can support science-based management in conservation areas by providing quantitative insights for managing tourism flows. However, part of our objective is also to highlight key limitations, including low tourist participation, technical challenges, and concerns related to the high spatial resolution of the data in the UNESCO Global Geopark.

Implementierung von GPS-Logger-Daten zur Besuchermonitoring im Karawanken UNESCO Global Geopark

ZUSAMMENFASSUNG

Die Koexistenz von Mensch und Natur ist ein zunehmend wichtiger Bestandteil der nachhaltigen Bewirtschaftung von Naturschutzgebieten. Wegweisende Naturschutzkonzepte konzentrieren sich darauf, diese beiden Aspekte zu integrieren, anstatt eine strikte Trennung vorzunehmen. Störungen des Gleichgewichts zwischen Mensch und Natur können sich sowohl auf den Schutz der natürlichen Ressourcen als auch auf das touristische Erlebnis auswirken. Um dies zu vermeiden, sind Pläne für das Management von Ressourcen, Infrastruktur und Touristenströmen erforderlich. Das HUMANITA-Projekt zielt darauf ab, innovative Lösungen zur Erfassung der touristischen Aktivitäten und deren Auswirkungen auf die Umwelt in ausgewählten Naturschutzgebieten in Mitteleuropa zu entwickeln. Es umfasst verschiedene Methoden zur Schätzung von Besucherzahlen, Hotspots und Aktivitäten. Wir haben 69 GPS-Logger im UNESCO Global Geopark Karawanken–Karavanke verteilt und Karten zur Besucherdichte und -intensität erstellt. Diese Studie zeigt, dass GPS-Logger-Tools ein wissenschaftlich fundiertes Management in Naturschutzgebieten unterstützen können, indem sie quantitative Erkenntnisse für die Steuerung von Touristenströmen liefern. Ein Teil unseres Ziels besteht jedoch auch darin, wesentliche Einschränkungen aufzuzeigen, darunter die geringe Beteiligung der Touristen, technische Herausforderungen und Bedenken hinsichtlich der hohen räumlichen Auflösung der Daten im UNESCO Global Geopark.

INTRODUCTION

Conservation areas are intended to serve a dual role in protecting biodiversity while also supporting recreational activities [1]. Ecotourism has grown due to cleaner air, reduced water contamination areas, as well as opportunities for enjoyment and inspiration [2], [3]. Two main factors increased the popularity of conservation areas: growing interest in outdoor recreation and the reopening of tourism after the COVID-19 pandemic in 2021 [4]. In recent years, overtourism has become increasingly common including overcrowding, exceeding carrying capacity, anti-tourism movements, touristification, environmental sustainability concerns, and the loss of cultural identity and local traditions [5]. It results not as a singular anomaly, but as the visible expression of a broader system characterized by excess, acceleration, and territorial imbalance [6]. In this context, the main

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challenge is to balance public access to the conservation areas with the protection of sensitive natural environments. Data on visitor behavior, environmental pressures, and ecological change enable more comprehensive and effective management of the area impacted by overtourism [1], [7]. Indeed, visitor monitoring strategies play a crucial role, capturing data such as the locations people visit, the routes they take, the time spent in each area, and other general information on recreational use [8], [9].

Over the years, a range of methods has been developed to measure tourism activity to capture the volume and the characteristics of recreational use [10]. There are two different types of tourism measurement: one based on the monetary value generated by tourism activities, and the other on tourist demand, including the number of visitors compared to social influence and penetration [11]. One example of the latter is the Travel Intensity Index, defined as the ratio between the total number of visitors and the local population [12]. However, the need to incorporate spatial data into planning is evident, as recreational experiences in protected areas are inherently "spatially conditioned" processes [7], [14]. Space provides a platform where social, ecological, infrastructural, and economic factors can be integrated and understood in relation to one another [13]. Understanding the spatial and temporal distribution of tourism helps to assess the extent and impacts on related resources [7], [9], [15]. Several phases have been identified within the last "25 years of tourist tracking," spanning the so-named pre-technology era and the three subsequent technological eras [15]. The earliest method for collecting spatial and temporal data involved asking visitors to record their own travel routes and times on paper maps, a process that often led to errors and imprecision [8]. Then, some technologies were developed for tourism monitoring [10], including Global Positioning System (GPS), Wi-Fi and Bluetooth tracking, Near Field Communication, and social media monitoring [8]. These tools avoid the time-consuming nature of traditional methods based on surveys and drawing trails on maps [16]. The most commonly used technology is GPS tracking [17], as a comparative study reported that GPS data provide more detailed and accurate information than traditional methods [18]. In 2005, response rates for GPS-based methods were already higher than those of traditional approaches, suggesting that they were perceived as less intrusive [19]. In 2012, the use of GPS tracking in the USA was described as an emerging technology, highlighting advantages over traditional methods, including the collection of reliable, accurate, and precise data [8]. Subsequent studies also described the advancement of GPS tracking in different contexts, compared to previous methods [7], [21], [22], [23]. GPS can be intended as a GPS tracking smartphone application, for example TraceMate [23], Catch-my-Day [24], floating smartphone data provided by a third-party company [25], or GPS logger [26]. They have been used in a variety of manners applicable to transportation and mobility [21], [24], [25] including sedentary behavior and health-related issues [27], wildlife ecology [29], [30], [31], and tourism management [32], [33]. GPS tracking has major relevance in the transportation sector, including the use of a variety of advanced data processing methods, machine learning algorithms, and novel semi-supervised deep learning approaches that are being actively developed [26], [27], [36]. Also, some projects have focused on collecting GPS track data and allowing the further use of this data. The "GeoLife" project collected 17,621 trajectories to use in mobility pattern mining, user activity recognition or location recommendation [34]. Some studies were based on the PPGIS tool called "MyDynamicForest" including GPS-tracked and drawn routes [35]. Although GPS tracking is not particularly useful for capturing the total number of visitors entering an area, it can still apply to relatively large and often inaccessible areas that are difficult to study using other methods [9]. Additional advantages include lower staff effort and independence from weather conditions [9]. When GPS tracking is used via tourists' mobile phones, some issues may arise due to users' lack of experience with smartphone functions, as they may use their phones mainly for calling and texting. This can lead visitors to leave the mobile phone setup unchanged or improperly configured, thereby preventing the acquisition of data [22]. Other problems can arise from the high cost of distributing a large number of devices, the risk of data loss, and constraints on visitor movement [22]. Dense forest cover, mountainous terrain, and deep canyons can significantly reduce the effectiveness of GPS in these applications [9], [38]. In such environments, spatial data may be lost due to signal obstruction, resulting in poor or incomplete tracking [8].

Specifically, GPS tracking is used in the identification of tourist behavior in conservation areas [10], [39], [40]. GPS tracking was described as a valuable tool for identifying off-piste ski touring ascent and descent routes and for estimating the extent to which users venture outside designated areas [9]. GPS tracking and graph theory were used to evaluate the structure and use of designated skiing zones [39]. GPS logger technology was also implemented to track backcountry recreation use in Denali National Park, Alaska, USA, as the park's large size and lack of trails make it difficult to identify travel patterns [37]. Within the Interreg Central Europe project HUMANITA, the development of a visitor monitoring strategy led to collection of GPS logger data in the Karawanken-Karavanke UNESCO Global Geopark (UGGp) at the border between Austria and Slovenia. The designation of UGGp is given to a unified geographical area of international geological significance, managed by combining conservation efforts with sustainable development [40]. Geotourism has attracted growing global interest [41], [42], [43] and is defined as a form of nature-based tourism that focuses on geology and the geological environment [44]. The international recognition of their touristic and natural resource values has created opportunities to promote geoconservation while supporting sustainable development [45], [46]. Considering their goals, UGGps require spatial planning for sustainable development within their territorial management plans [47]. A literature review on the application of Geographic Information Systems (GIS) in UNESCO Global Geoparks highlighted their limited use in both territorial characterization and management strategies. Most research focused on GIS-based thematic mapping (16 publications) and remote sensing techniques (7 publications), followed by digital elevation and terrain models, 3D modelling, multicriteria analysis, and related approaches [47]. A significant data gap was identified in the availability of reliable, local, same-day data, which is essential for stakeholders to make informed strategic decisions in tourist destinations [10]. In some UNESCO sites, large-scale questionnaires have been deployed [48], alongside mobile phone data [5], passive GPS data [10], and geotagged photographs [14]. The application of GPS loggers within a UGGp constitutes a gap in the state-of-art-of the research considering the high conservation value of these sites and high degree of tourist involvement.

This article aims to move the application of GPS tracking data in the study of tourist behavior in UGGps one step further by applying GPS logger tools to visitor monitoring. Building on previous studies that applied GPS loggers in different contexts, we aim to evaluate tourist behavior in terms of intensity and spatial density including limitations and concerns within a UGGp. Loggers can facilitate evidence-based decision-making and enable more focused management of visitors, contributing to the promotion of sustainable and efficient tourism practices.

METHODS

1.1 Study Area

The Karawanken-Karavanke UNESCO Global Geopark was established in 2013 as a member of the European Geoparks Network and the Global Geopark Network. In 2015, the geopark became an official UNESCO programme recognized as a UGGp [49]. This geopark covers an area of 1,067 km² and extends across the border between nine municipalities in southern Austria and five municipalities in northern Slovenia. It features remarkable geological diversity between the Alps and the Dinarides that goes back 500 million years [16], [49]. The geopark is within an alpine ecosystem characterized by steep, rocky cliffs on the Austrian side and alpine meadows that descend into the Slovenian valleys [49].

The Mount Petzen/Peca hotspot area is a carbonate mountain range that lies along the border between Austria and Slovenia, with a key crossing at the Kniepssattel/Končnikovo sedlo pass (2,012 m a.s.l.) (Figure 1). Its terrain is shaped by a karst system, where water erosion has created a complex network of cracks, caves, and underground drainage pathways. On the Slovenian side, the southern slopes are part of the Natura 2000 network, designated in 2008 under the Habitats Directive. This area includes the Grintovci Special Protection Area, which safeguards rare bird species under the Birds Directive. The mountain hosts rich biodiversity: springs and wet meadows provide habitat for uncommon plant species such as the common butterwort and several wild orchids. It is also home to sensitive wildlife, including the hazel grouse, Eurasian pygmy owl, and golden eagle.

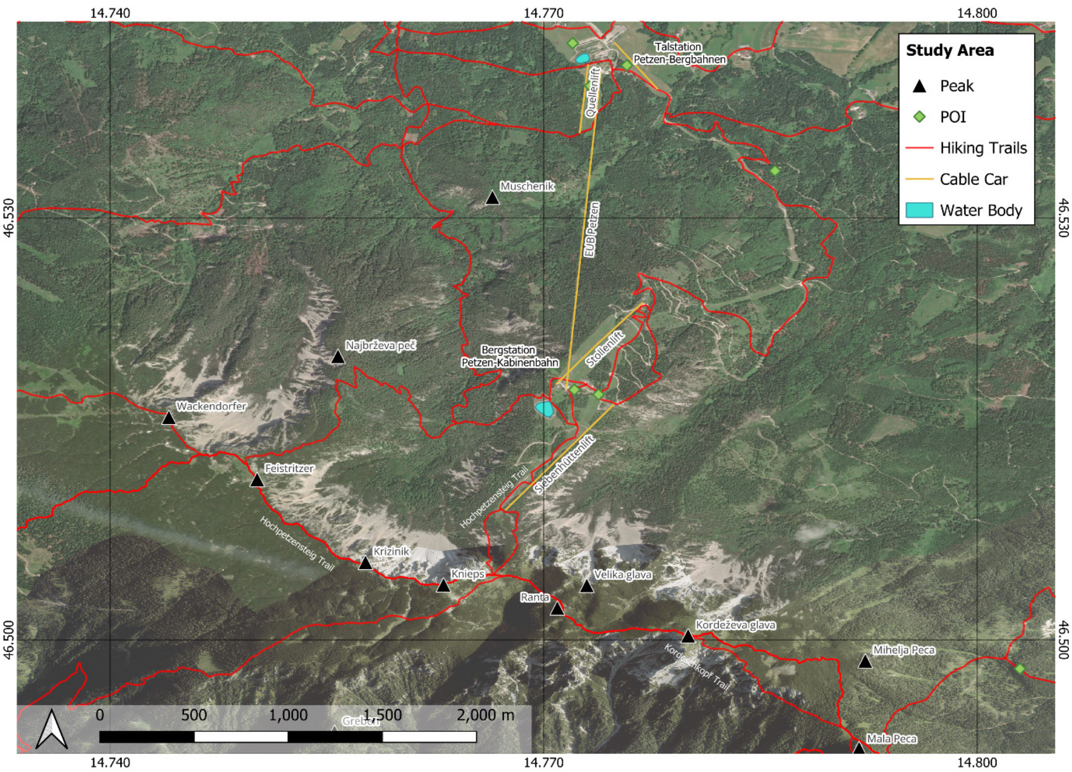

Fig. 1

Figure 1: Study area in Mount Petzen/Peca area.

Abbildung 1: *Untersuchungsgebiet auf der Petzen/Peca*

The proximity of major airports in Klagenfurt and Ljubljana allows easy access via the public transport network. Due to this accessibility, the Geopark is widely used for outdoor recreation, including hiking, cycling, paragliding, and rock climbing in summer, as well as winter tourism, with around 15 km of ski slopes served by the Petzen cable car [49]. These activities are supported by various tourist facilities, such as chalets, guesthouses, and hotels [16]. In 2022 the Austrian side recorded over 3 million visitors, while the Slovenian side accounted for approximately 55,000 tourists [50], [51]. Between 2005 and 2015, Austria attracted around 70% of park visitors; however, Slovenia experienced a notable increase in tourism, rising by about 37% in 2022. Domestic visitors make up roughly 65% of the total. Seasonally, summer has the highest numbers, with peak months in July and August averaging about 7,400 and 8,800 arrivals per month respectively. In contrast, during the winter season (November to April), the geopark hosts a total of around 13,100 visitors.

1.2 Data Collection

Forty Renkforce GT-730FL-S GPS loggers were provided to the ticket office at the cable car valley station (Talstation Petzen Bergbahnen). The data collection initiative was promoted by the employers and posters around the area. Tourists passing through the ticket office for the cable car during working hours were asked over four specific days whether they would like to participate in the data collection. To encourage greater participation, a free ski pass was offered as a prize in a random drawing. Those who agreed were asked to record metadata for each deployed GPS logger, including age, gender, and group size.

For calibration and acquisition of a GPS signal, the devices were switched on in advance of tourist departures. In total, 69 GPS loggers were distributed among pedestrians and hikers at the cable car station. Some GPS loggers were switched on and off during use, resulting in 75 tracks being downloaded: 15 on 7/19/2024, 28 on 8/26/2025 representing 56 people in total, and 32 on 9/19/2025 representing 53 people. For 7/19/2024, the group size data was not collected. Another data collection session was conducted, but no data were collected, likely due both to limited staff engagement and to tourists' concerns about carrying GPS loggers. The devices were set to record the GPS location at 5-second intervals, not only to record the spatial movement, but also to represent higher concentrations of points if visitors stayed at a location for a longer period of time.

1.3 Data Cleaning and Analyses

The literature reports several manual data-cleaning procedures for GPS logger data [7], [10]. In this study, our aim was to develop an automated tool to support the independent management of the geopark. Therefore, we implemented data-cleaning in Python [18] to enable a more efficient and streamlined processing workflow.

We applied four spatial filters in Python, iteratively, three times. The distance and speed filters were partly based on the methodology of [17], while the other parameters were determined through iterative testing and adjustments. First, a minimum distance filter of 2 m was applied between two consecutive points. Since the GPS loggers recorded data every 5 seconds, this allows for high-resolution data but can also introduce potential inaccuracies during short breaks. A short recording interval may lead to an overestimation of stay time, particularly in cases of slow walking speeds or in steeper trail sections. Second, a maximum distance of 50 m between two consecutive points was set, as pedestrians would not normally cover more than this distance in 5 seconds, and points exceeding this threshold were considered indicative of signal distortion. Third, a maximum speed filter of 6 km/h was applied, as higher speeds were considered signal errors, since they would exceed the typical walking speed of a person. Fourth, isolated points were identified using a spatial filter: any cluster of fewer than five points within a 50-m radius was removed. This threshold was chosen based on a visual inspection of the raw data and was considered appropriate for our data distribution. Finally, the tracks were subjected to a final quality check in QGIS [52]. Three GPS tracks were manually adjusted through the Move Feature tool in QGIS, since they were displaced by several meters from the only plausible trail, and seven tracks were manually removed due to irregular GPS points that the Python cleaning procedure could not detect. These anomalies were likely caused by signal interference from the cable car, as the issue mainly occurred on trails nearby.

A descriptive analysis was carried out in R, including a statistical summary of distance of trips and travel time for each track [53]. To examine the spatial distribution of tourists, the density of recorded GPS track points and their stay times were analyzed using QGIS. The density map shows the areas with the highest tourist presence and the intensity map indicates the locations with the longest duration of stay. The results are expressed as tourist stay per cell and the number of visitors per cell, following a workflow also adopted by [11], offering an improved understanding of touristic hotspots. The density map was generated using the Heatmap tool, applying a Kernel Density Estimation approach [54], as also implemented in previous studies [10], [15], [35], [39]. A search radius of 10 m was applied, with an output raster resolution of 0.10 and meters used as the unit to estimate the spatial density of point data. The intensity map was generated by calculating the mean stay time in Python, resulting in a raster heatmap with a spatial resolution of 30 m. Each track was analyzed individually, and each point was assigned to a grid cell. For each cell, all points from the track falling within that cell were considered, and the stay time was computed as the difference between the maximum and minimum timestamps of those points.

RESULTS

The analyses were conducted on 68 GPS tracks collected in the geopark. On average, a distance of 6.5 km was covered (min = 0.11 km, max = 15 km, SD = 4.32 km), and the tracks lasted an average of 197 minutes (min = 3 min, max = 421 min, SD = 112 min). Short distances and durations were observed near restaurants, where tourists likely switched off the devices during break times. These tracks were retained, as they were not considered a source of bias for the analysis.

The density map represents a heatmap of the GPS logger data (Figure 2). The scale is standardized, ranging from 0 (low intensity) to 100 (high intensity). To facilitate interpretation, the map is displayed together with viewpoints, points of interest, the cable car route, and hiking trails. We highlight four points of interest including two viewpoints, the Panoramarestaurant and the Alte Zollhütte. The latter is a historic alpine hut that has been converted into a restaurant and mountain refuge on Mount Petzen, offering panoramic views and a strategic location along hiking and tourism routes. The Panoramarestaurant is a modern summit restaurant focused on views and tourism services at the top of the area. The highest-intensity hotspot is located around the cable car valley station. During peak hours, this area becomes particularly dense, likely due to its role as the primary starting point of the cable car and the presence of a bike rental shop and restaurant. Consequently, the cable car mountain station (Bergstation Petzen-Kabinenbahn) experiences high visitor concentration; however, density decreases more rapidly there, as visitors spread out along different routes to engage in various activities. The results obtained at the cable car valley station are not shown on the map, as they were considered prone to error. This is because the GPS loggers were switched on before participants began their trip, and some devices were found to still be running afterward. At the summit station, an artificial lake for snow production in the winter season is surrounded by several resting areas, where many visitors enjoy the lake's summer recreational facilities. The Hochpetzensteig circular route is frequently used in two variants: from the lake along the ski slope or a forest road towards a resting area at the top station of the Siebenhütten T-bar lift. Most visitors turn back at the Knieps Saddle, representing an easy turning point to the lake without reaching one of the peaks. Other visitors either complete the circular trail, passing the Knieps towards the Petzen summit (Feistritzer), and descending along the Hochpetzensteig back to the lake or they turn left at the Knieps saddle towards Kordeschkopf, a very popular destination also from the Slovenian side of Mt. Petzen/Peca. Visitor density remains low in the upper sections of the mountain massif compared to the lower sections closer to the infrastructure facilities. The map highlights some instances where GPS points deviate slightly from the trail network, likely due to signal-related inaccuracies.

The intensity map (Figure 3) shows the visitor stay time in 30-m resolution pixels. Stationary visitor stays ranged from less than 2 minutes to 50-120 minutes. It is developed using the same legend elements as the density map to facilitate comparison and the scale is standardized. Visitors spent between 60 and 170 minutes at the cable car valley station, likely due to the presence of facilities such as service areas (ticket office, bike rental, bike wash) and a restaurant, or possibly as a result of the previously mentioned GPS-related issues. At the cable car mountain station, visitors mainly rested around the lake area, with stay times ranging from 2-10 minutes up to 25-50 minutes. Visitors tended to move to the eastern side of the cable car area, where longer stay times are associated with the presence of restaurants, huts (Panoramarestaurant and Alte Zollhütte) and the Geopark visitor center (Geo.Dom). Many times, the GPS signal was lost around this area, likely when visitors entered the buildings. Notably, on the western side of the cable car mountain station, a viewpoint was associated with an average stay time of approximately 10-25 minutes. At the trail bifurcation from the Siebenhütten rest area towards the Knieps Saddle, visitors tended to spend more time on the left-side trail with various stops until they reach the Knieps, probably due to an easier and better trail view. Along the trail

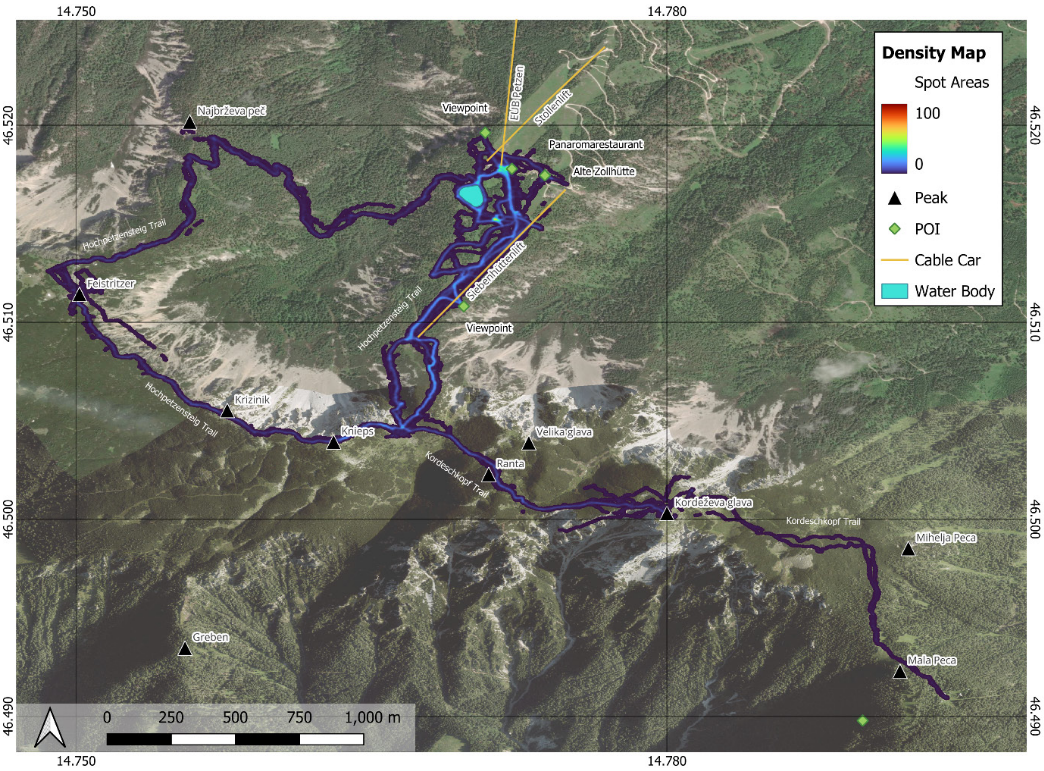

Fig. 2

Figure 2:
Density map of visitors in the Mount Petzen site.

Abbildung 2:
Besucherdichtekarte des Gebiets am Berg Petzen.

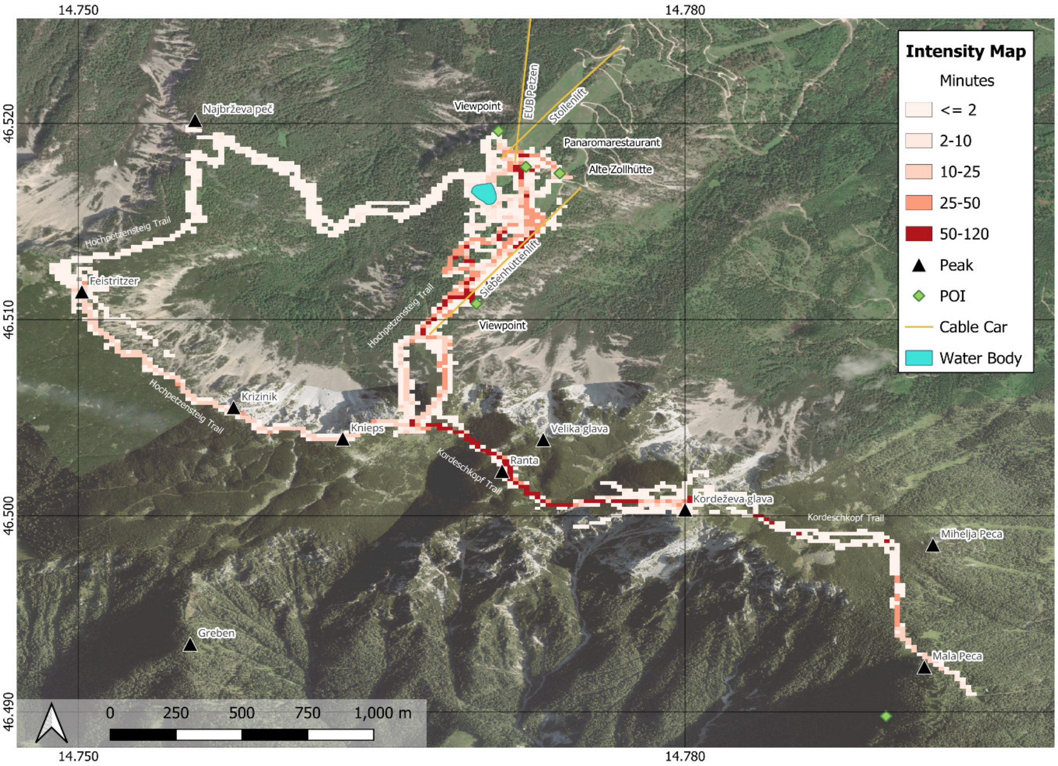

Fig. 3

Figure 3: Intensity map of visitors in the Mount Petzen site.

Abbildung 3: *– Intensitätskarte der Besucher im Gebiet des Berges Petzen.*

leading to the summit, several viewpoints overlapped with areas of longer stay times. Also, visitors appeared to spend more time along the trail leading to the summit, likely because they took breaks to rest or stop at viewpoints. The Mt. Petzen/Peca summit (Feistritzer) itself showed a 30-m pixel corresponding to an average stay time of around 25-50 minutes. Finally, the Kordeschkopf trails showed high stay times across the entire network, which may be explained by some GPS tracks that were not entirely accurate in that area.

DISCUSSION

In the tourism industry, understanding where and when tourists visit provides valuable insights for selecting the most suitable locations to develop new activities [32]. Managers can define visitor groups and design more targeted, diverse offerings that better align with the needs and interests of different audiences [13]. To address these interests, we aimed to study recreational use patterns by investigating movements within a UGGp rather than simply reporting them [8]. Given the global importance of these areas, more targeted research using GPS tracking should be conducted through multiple case studies, as the variability among sites is considerable. The results of this analysis demonstrate how GPS logger technology can provide high-resolution data with a wide range of potential applications. The density and intensity maps help in better understanding visitor behavior and trail preferences, including their temporal patterns. Indeed, they give insights into the most frequented trails and the hotspot areas for tourists. The former helps to identify where human–nature interactions are more concentrated and where greater attention is needed to monitor and manage the potential impact of tourists on these areas. The latter is also important for this purpose, but it additionally helps to better understand the type of tourism that characterizes the area. Visitors may seek solitude and relaxation, or more social experiences such as playing and picnicking [37]. Indeed, understanding human movement and behavior in parks is embedded within a social-ecological systems framework [37]. Our study area points to a predominantly family-oriented tourism pattern, concentrated in lower-elevation areas, with higher visitor density and intensity around shared facilities such as restaurants, huts, and picnic sites. This information supports informed conservation area management, improving the coexistence between tourism activities and conservation of natural resources.

In the Mount Petzen area of the UGGp, it is evident that the highest visitor densities occur in zones with the greatest concentration of services and infrastructure, such as the cable car stations, gear rental points and washing facilities, as well as restaurants and huts. Most tourists remain near the cable car mountain station and do not move far along the trails. Consequently, picnic areas, lake surroundings, and huts frequently experience high visitor density. Higher-elevation areas, such as those near the summit, are locations where visitors tend to stop briefly at viewpoints or to rest. These areas do not experience the same levels of crowding as the lower, more accessible zones.

Despite these findings, some limitations were encountered during data collection, including low tourist participation. Considering the large number of annual visitors to the UGGp, the low number of 69 devices distributed may limit the representativeness of the data. For this reason, we limited the extent of generalizations drawn from the study, focusing instead on identifying key issues and potential areas for future improvement. Our limitations may be related both to tourist reluctance to participate in the study and to insufficient collaboration with the third-party partner responsible for distributing the GPS loggers. Other studies encountered related problems describing that some visitors declined to participate due to privacy concerns or unfamiliarity with tracking technologies [7], [22], [55]. A possible solution includes strengthening communication activities that incorporate education and awareness-raising, which would benefit both park staff and visitors and contribute to more efficient data collection. Developing simple materials such as step-by-step instructional flyers, short videos, or QR codes explaining how to use the device, as well as checklists for staff outlining what to communicate to visitors, could support more efficient data collection. These measures would also help stakeholders better understand the innovation and practical benefits of the tool. These types of activities are particularly important given that GPS loggers are managed directly by tourists, which can introduce certain biases in data collection. For instance, awareness of being tracked may influence visitor behavior [9]. In our study, we also observed that devices were often switched on and off during use, which can lead to tracking biases that are difficult to identify and correct. This may occur because visitors, when stopping at areas such as picnic sites or restaurants, choose to pause the tracking without being aware that the time spent at these locations is also important for identifying recreational patterns. This highlights another example of how the purpose of the technology and the objectives of the study need to be clearly and effectively communicated.

Another limitation of this study was the incomplete acquisition of metadata, resulting from insufficient collaboration and active involvement of park staff. Indeed, not all GPS loggers were properly registered, even when the tracking data were recorded. This highlights an additional challenge when relying on third parties for data collection. GPS logger data should be analyzed in combination with questionnaire surveys that provide a socio-demographic profile of the population and visitors who decline to participate, in order to assess the representativeness of the dataset [21], [22]. Participants may be biased, as they tend to be younger, more technology-oriented, stay longer, or travel from greater distances [22]. Again, this highlights an issue that can arise when data collection is delegated to third parties, particularly when the importance and relevance of the study is not particularly clear to them.

Finally, signal deviation was a challenge. The automatic cleaning in Python only addressed point-level errors and did not account for the spatial context of the tracks. As a result, certain anomalies—such as GPS tracks deviating from plausible trails—cannot be resolved automatically and require manual intervention. One of the primary objectives was to make data processing as automated as possible, so that this approach can be accessible to a broader range of users. However, this is not always guaranteed with this type of data, especially in natural environments and in areas with cable car infrastructure, where signal distortions are more likely to occur. An initial data cleaning and preprocessing phase is necessary to reduce potential bias and improve the reliability of the results. Even so, the Kordeschkopf trails illustrate that, despite preprocessing and filtering, misleading data can still persist when using high-resolution technologies.

CONCLUSION

Analyzing the data quantitatively (numerical estimates) and qualitatively (mapping) offers a clearer understanding of tourist flows and behavior. Using GPS technologies offers a concrete approach to managing conservation areas, making observations possible at high-resolution. However, several challenges can arise in the deployment of GPS loggers. These include tourists' reluctance to carry the devices, limited involvement of park staff, signal reception issues, and the time and staff skills required for data cleaning. These factors represent important limitations of using this tool in the context of a UGGp. UGGps are often characterized by large areas and high-variability landscapes. Here, GPS loggers can provide valuable information for management purposes. However, their level of resolution may sometimes be too high to represent the diversity of the park. Within this framework, we encourage implementing an approach that integrates multiple technologies to manage visitor flows in UGGps. GPS loggers make it possible to identify the most likely movement patterns, stopping areas, and hotspot locations. However, they do not provide information on the number of tourists experiencing specific areas, as automatic counters do. Similarly, they do not offer insights into tourists' environmental sensitivity or attitudes toward nature, which can instead be captured through surveys. Finally, the limitations mentioned above should be considered alongside those of other tools, with the aim of identifying cross-method solutions. Therefore, combining different tools allows for a more holistic view of visitors within the area than single approaches [10], [56]. This knowledge can support the planning of new infrastructure or recreational facilities in order to address a sustainable form of tourism.

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ABOUT THE AUTHORS

Sabrina Muscolino
UNESCO Chair on Sustainable Management of Conservation Areas
ICEB, CUAS
Villach, Austria
E-Mail: s.muscolino@cuas.at

Lilia Schmalzl
UNESCO Chair on Sustainable Management of Conservation Areas
ICEB, CUAS, Villach
Austria

Julian Greiler
UNESCO Chair on Sustainable Management of Conservation Areas
ICEB, CUAS, Villach
Austria

BACK TO CONTENT

Short Notes

Advancing biodiversity research in the agroecosystem: Project BioMonitor4CAP in focus

Daniel Dalton, Vanessa Berger, Jessica Fuchs, Gernot Paulus, Stefan Ruess, Ulf Scherling, Klaus Steinbauer, Ilja Svetnik

ABSTRACT

The EU Biodiversity Strategy 2030 recognizes farmers' dual role in safeguarding and impacting biodiversity. Within this policy context, the Horizon Europe project BioMonitor4CAP addresses monitoring of agroecosystem biodiversity and stakeholder-informed policy design to contribute perspectives and guidance in advance of the next Common Agricultural Policy period. The project integrates above- and below-ground indicators—pollinator insects, farmland birds, soil microbiota, and landscape structure—by pairing traditional methods with state-of-the-art tools across a network of European research sites. In Carinthia, six sites spanning low-elevation and high-elevation areas are used for testing traditional and state-of-the-art workflows targeting farmland birds, pollinator insects, soil communities, vegetation plots, and landscape structure. Sampling timing is based on a growing degree-day (GDD) approach. Carinthia University of Applied Sciences leads regional implementation, device feasibility testing, GDD scheduling, and remote sensing case studies, contributing to systematic reviews, indicator frameworks, and data infrastructure. A socio-economic component of the project engages farmers, advisors, and policymakers through focus groups, co-creation workshops, and a discrete choice experiment on subsidy trade-offs, complemented by mapping a Europe-wide network of ~600 agrobiodiversity observatories. Early findings highlight operational feasibility, ethical considerations, and context dependence of methods; regulatory and site constraints necessitated adaptive designs. BioMonitor4CAP is synthesizing evidence to deliver results-based monitoring guidance and policy options that reconcile practicality of monitoring approaches with conservation effectiveness. The project underscores that no single measure fits all farms, but co-designed, evidence-based approaches can align agricultural production, biodiversity outcomes, and circular economy goals for Europe.

KEYWORDS

- Agroecosystem
- Biodiversity monitoring
- Common Agricultural Policy
- Socio-economics
- Indicator species

Förderung der Biodiversitätsforschung im Agroökosystem: Projekt BioMonitor4CAP im Fokus

ZUSAMMENFASSUNG

Die EUBiodiversitätsstrategie 2030 erkennt die doppelte Rolle der Landwirte bei der Bewahrung und der Beeinflussung der biologischen Vielfalt an. Vor diesem politischen Hintergrund befasst sich das HorizonEuropeProjekt BioMonitor4CAP mit der Überwachung der Biodiversität in Agrarökosystemen und der an Stakeholdern orientierten Politikgestaltung, um Perspektiven und Leitlinien im Vorfeld der nächsten Förderperiode der Gemeinsamen Agrarpolitik (GAP) bereitzustellen. Das Projekt integriert ober- und unterirdische Indikatoren – bestäubende Insekten, Feldvögel, Bodenmikrobiota und Landschaftsstruktur – durch die Kombination traditioneller Methoden mit modernsten Werkzeugen über ein Netzwerk europäischer Forschungsstandorte hinweg. In Kärnten werden sechs Standorte, die Tieflagen und Hochlagen abdecken, für Tests traditioneller und moderner Arbeitsabläufe zu Feldvögeln, Bestäuberinsekten, Bodengemeinschaften, Vegetationsaufnahmen und Landschaftsstruktur genutzt. Die zeitliche Planung der Probenahmen basiert auf einem Gradtag(GDD)Ansatz. Die Fachhochschule Kärnten leitet die regionale Umsetzung, die Praxistests von Geräten, die GDDTerminplanung und FernerkundungsFallstudien und leistet Beiträge zu systematischen Übersichten, Indikatorenrahmen und Dateninfrastruktur. Eine sozioökonomische Komponente des Projekts bezieht Landwirtinnen und Landwirte, Beratende und politische Entscheidungsträger durch Fokusgruppen, CoCreationWorkshops und ein DiscreteChoiceExperiment zu FördermittelTradeoffs ein; ergänzt wird dies durch die Kartierung eines europaweiten Netzwerks von rund 600 AgrobiodiversitätsObservatorien. Erste Ergebnisse heben die praktische Umsetzbarkeit, ethische Erwägungen und die Kontextabhängigkeit der Methoden hervor; regulatorische und standortbezogene Einschränkungen machten adaptive Designs erforderlich. BioMonitor4CAP synthetisiert Evidenz, um ergebnisorientierte MonitoringLeitlinien und politische Handlungsoptionen zu entwickeln, die die Praktikabilität von Monitoringansätzen mit der Wirksamkeit des Naturschutzes in Einklang bringen. Das Projekt unterstreicht, dass es keine Maßnahme gibt, die für alle Betriebe passt; gemeinsam entwickelte, evidenzbasierte Ansätze können jedoch landwirtschaftliche Produktion, Biodiversitätsergebnisse und Ziele der Kreislaufwirtschaft in Europa miteinander verbinden.

BACKGROUND AND DEVELOPMENT

The European Union Biodiversity Strategy 2030 (EU BDS) underlines the role that farmers play in preserving biodiversity while at the same time acknowledging that certain agricultural practices are key drivers of biodiversity decline and soil degradation. Farmland birds, pollinator insects, and soil microbiota are key indicators of the health of agroecosystems and are vital for food security. In the EU BDS, one target is to ensure that at least 10 % of agricultural area within the European Union contains high-diversity landscape features (e.g., hedgerows, flower strips, fallow, buffer strips, ponds, and non-productive elements), supporting these indicator species [1].

The EU Common Agricultural Policy (CAP) requires agricultural producers to comply with nature protection regulations such as the Birds Directive and Habitats Directive, while formally protecting against environmental degradation in conservation areas within the agricultural landscape [2], [3], [4]. To support farmers' implementation of environmentally friendly practices, the CAP is the primary tool to provide financing mechanisms for compensation and incentivization. Program cycles are periodically revisited. The current CAP period extends through 2027.

The Horizon Europe-funded project "Advanced biodiversity monitoring for results-based and effective agricultural policy and transformation" (BioMonitor4CAP) is designed to address monitoring biodiversity in European agroecosystems in parallel with analysis of farmer and policy maker perspectives on monitoring. Project outputs are intended to provide insights to help guide the policies of the next CAP period. Key indicator groups encompassing above-ground and below-ground biodiversity are in focus: pollinator insects, farmland bird species, soil microbial communities, and landscape structure. Indicators should represent key aspects of above-ground and below-ground biodiversity. During the field work, a comparative monitoring approach is implemented where traditional monitoring methodologies are performed alongside state-of-the-art approaches for each indicator group. In order of monitoring intensity, research sites are designated as "major," "selected," and "demonstration" grids representing a variety of land use situations.

BioMonitor4CAP activities are divided into three research themes representing scientific topics, in addition to project management, outreach, and ethics. The research themes address: 1) conceptualization and implementation of field monitoring activities; 2) detailed investigation of agrobiodiversity indicators, programs, and policies; and 3) socio-economic research.

PROJECT PARTNERS

BioMonitor4CAP includes 23 participating organizations across nine EU countries—plus the UK and Peru—and represents diverse major agroecological regions of Europe (Figure 1). The lead partner is Leibniz Institute for the Analysis of Biodiversity Change, nested within the Museum Koenig, Bonn, Germany. Project partners include public and private research institutes, universities, and agricultural societies (Table 1). Inclusion of Peruvian field research sites is designed as independent validation of the applicability of selected methodologies. All partners provide specialized expertise and connections to diverse stakeholder perspectives. Faculty involvement from Carinthia University of Applied Sciences (CUAS) allows regional application of research techniques and promotes Austrian stakeholder perspectives in project activities.

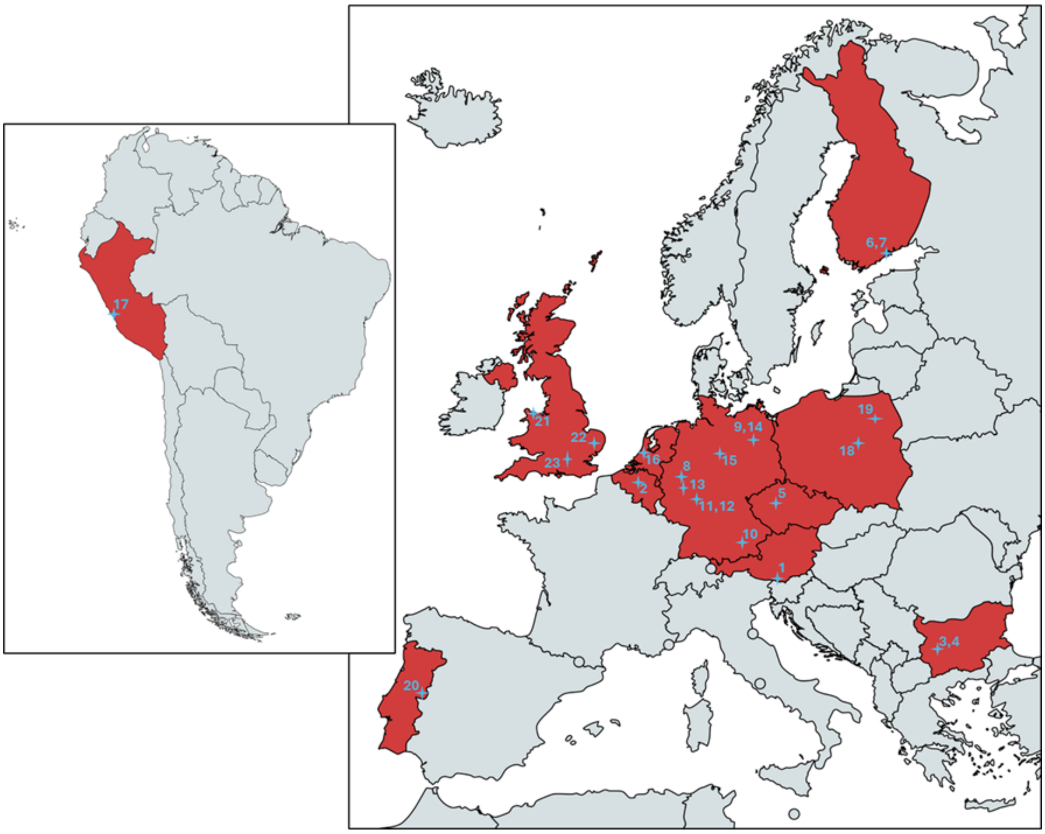

Fig. 1

Figure 1:
Participating countries in BioMonitor4CAP. South American continent (inset) is not shown to scale. Source: Maps created with https://www.mapchart.net under a Creative Commons Attribution-ShareAlike 4.0 International License.

Abbildung 1:
Teilnehmende Länder in BioMonitor4CAP. Der südamerikanische Kontinent (Ausschnitt) ist nicht maßstabsgetreu dargestellt. Quelle: Karten erstellt mit https://www.mapchart.net unter einer Creative Commons Attribution-ShareAlike 4.0 International Licence.

Tab. 1

Reference number	Acronym	Country	Institution name
1	CUAS	Austria	Carinthia University of Applied Sciences
2	FE	Belgium	Farm Europe
3	BSPB	Bulgaria	Bulgarian Society for the Protection of Birds
4	IBER	Bulgaria	Institute of Biodiversity and Ecosystem Research
5	CSO	Czechia	Czech Society for Ornithology
6	LUKE	Finland	Natural Resources Institute Finland
7	UH	Finland	University of Helsinki
8	Bayer	Germany	Bayer AG
9	LfU	Germany	Brandenburg State Office for the Environment
10	IDMT	Germany	Fraunhofer Institute for Digital Media Technology
11	DLG	Germany	German Agricultural Society
12	IVA	Germany	German Crop Protection Association
13	LIB	Germany	Leibniz Institute for the Analysis of Biodiversity Change
14	ATB	Germany	Leibniz Institute of Agricultural Engineering and Bio-economy
15	SUH	Germany	University of Hildesheim
16	S4G	Netherlands	Space4Good
17	UCSUR	Peru	Scientific University of the South
18	IRWIR PAN	Poland	Institute of Rural and Agricultural Development Polish Academy of Science
19	WSA	Poland	School of Agribusiness in Lomza
20	F4S	Portugal	Food4Sustainability
21	BU	UK	Bangor University
22	BTO	UK	British Trust for Ornithology
23	NM	UK	NatureMetrics

Table 1:
Project partners and associated partners participating in BioMonitor4CAP. Reference number matches the marker identifiers in Figure 1.

Tabelle 1:
Projektpartner und assoziierte Partner, die an BioMonitor4CAP teilnehmen. Die Referenznummer stimmt mit den Markerkennungen in Abbildung 1 überein.

STUDY SITES IN AUSTRIA

BioMonitor4CAP researchers utilize seven study sites located in Austria. One site is located in Lower Austria, a Bayer ForwardFarming field (Bayer Austria GmbH) that serves as an affiliated learning site for the Hollabrunn Agricultural Vocational School. The remaining six sites are located in Carinthia, and personnel from the CUAS Interdisciplinary Center for Ecosystem Services and Biodiversity (ICEB) perform site visits and data collection (Figure 2). Project-wide, study sites should include areas containing carbon-rich soils, grassland habitats, and agroforestry sites, with some sites located within conservation areas or other biodiversity-rich regions. The Carinthian study sites represent these principles. Most sites are rich in habitat diversity, including areas with diverse tree species, commercially planted wine grapes and vegetables, and grassland areas managed with low-input techniques. The high-elevation sites are adjacent to the Salzburger Lungau & Kärntner Nockberge Biosphere Reserve. One low-elevation site is a degraded marsh that is in early phases of restoration. All sites are nested within the agroecosystems of their respective regions.

Fig. 2

Figure 2: BioMonitor4CAP study sites in Carinthia, Austria. Blue-colored icons indicate high-elevation sites centered around Ebene Reichenau, and red-colored icons indicate low-elevation sites in proximity to Klagenfurt. Source: KAGIS.

Abbildung 2: *BioMonitor4CAP-Untersuchungsflächen in Kärnten, Österreich. Blaue Symbole zeigen hochgelegene Stätten rund um Ebene Reichenau an, rote Symbole zeigen niedrig gelegene Stätten in der Nähe von Klagenfurt. Quelle: KAGIS.*

By design, BioMonitor4CAP study sites should contain at least five sampling points arranged in a regular pattern within a 1000 m × 1000 m square, with at least 200 m separating the points. In Carinthia, geographic factors and sizes of study sites required modification of the intended sampling point layout at nearly all sites.

In the project, indicators are evaluated using traditional approaches in comparison to state-of-the-art approaches. To monitor pollinator insects, certain institutions perform lethal trap captures, followed by expert-based identification, for comparison against camera trapping. No traditional lethal insect collection traps are used at CUAS-managed sites; to compensate for this, we apply supplemental insect camera trapping arrays for experimental testing. For birds, traditional point count surveys are performed by experts during the breeding season in parallel to technology-based automated acoustic recording. For soils, standard soil samples are collected alongside soil environmental DNA collections for inference on the soil fungal, bacterial, and invertebrate communities. For landscape features, project partners gather earth observation data at specific points of the season, and UAS flights occur at certain sites, based on the capacities of the research team managing the field work. At CUAS, the research team at the ICEB Spatial Informatics for ENvironmental Applications (ICEB-SIENA), perform UAS missions at three research sites.

To coordinate sampling strategies across the different European climates, a growing degree-day (GDD) approach is used (Figure 3). GDD can help explain development of organisms based on the amount of heat accumulated at a site over time. To calculate GDD, at least two recent years of daily weather data were drawn from weather stations near field sites to approximate average daily temperatures at research grids. The simplest calculation—called the *max + min method*—uses the daily high and low temperatures while accounting for the base temperature, T_{base} [5], a theoretical value below which plant or insect development does not occur, and a daily maximum temperature threshold, T_{max}, as an upper limit to physiological development. Calculations provide daily degree-day values that are added to the previous day's running cumulative total, producing GDD. Daily degree-day values of less than 0 are assigned a value of 0. T_{base} and T_{max} are usually assumed at 10 °C and 30 °C, respectively, while T_{base} of cool season grasses is adjusted to 0 °C [6]. Actual temperatures limiting development of individual species can be calculated after studies under controlled conditions [7], [8]; however, simple GDD calculations are suitable for general forecasting. In BioMonitor4CAP, a benchmark 300-GDD monitoring interval was chosen after analyzing GDD accumulations near field sites, assuming T_{base} and T_{max} of 10 °C and 30 °C, respectively.

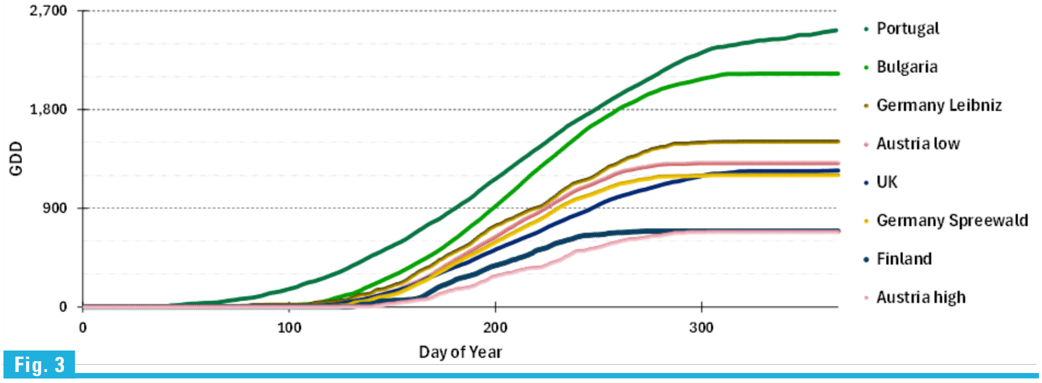

Fig. 3

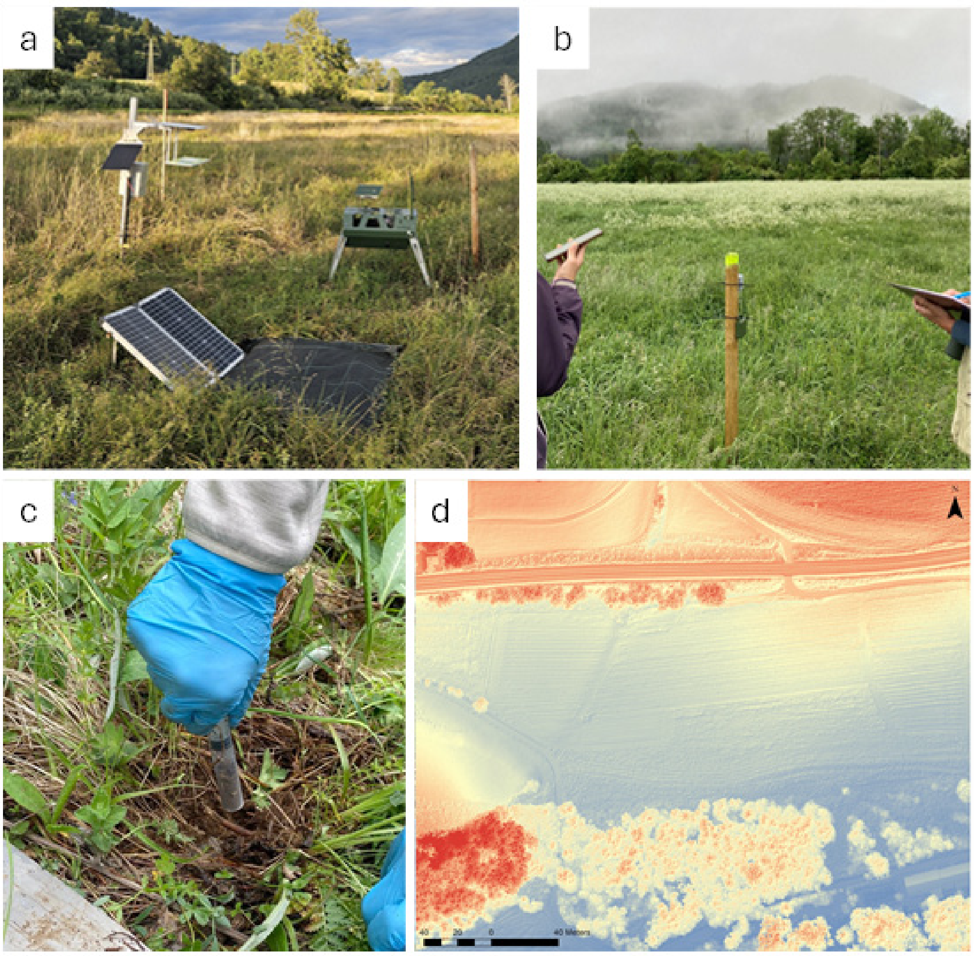

Fig. 4

Figure 3: Growing degree-day (GDD) curves for regions containing BioMonitor4CAP study sites.

Abbildung 3: *Kurven der Wachstumsgradtage (Growing Degree-Days, GDD) für Regionen mit BioMonitor4CAP Untersuchungsflächen.*

Figure 4: Advanced methods for biodiversity monitoring at BioMonitor4CAP field sites in Carinthia. Optical sensors (a), acoustic sensors and point counting (b), soil sampling (c), and UAS flights (d) all provide comparative approaches for monitoring. Sources: Photos © Ilja Svetnik (a); Daniel Dalton (b, c); digital surface model © ICEB-SIENA, Carinthia University of Applied Sciences (d)

Abbildung 4: *Moderne Methoden für das Biodiversitätsmonitoring an BioMonitor4CAP-Untersuchungsflächen in Kärnten. Optische Sensoren (a), akustische Sensoren und Punktzählungen (b), Bodenprobenahme (c) und Drohnen-Flüge (d) liefern vergleichende Ansätze für das Monitoring. Quellen: Fotos © Ilja Svetnik (a); Daniel Dalton (b, c); digitales Oberflächenmodell © ICEB-SIENA, Hochschule Kärnten (d)*

CUAS contribution: At the project outset, the ICEB Management of Conservation Areas (ICEB-MCA) team calculated GDD curves for each European region involved in the project. This helped determine the optimal timing of field monitoring activities prior to implementation. We test about 15 different devices or approaches spanning the four indicator groups and evaluate each of them for scientific performance, ecological suitability, operational criteria, analytical factors, ethical issues, and strategic value (Figure 4). CUAS was among three project partners who used the experimental DIOPSIS sensor—an experimental automated camera trap for insects—in 2025. With the remote sensing expertise of ICEB-SIENA, we are uniquely situated to provide Carinthian case study information on landscape structure [9].

FIELD TESTING

The advancement of agrobiodiversity monitoring tools is a key goal of BioMonitor4CAP. This theme is realized through conceptualization and implementation of monitoring at field sites (Table 2). Feasibility analysis of the various technologies was conducted based on past work. Configurations of devices—along with their settings—were adjusted based on initial test runs.

Tab. 2

Sampling Round	SR1						SR2						SR3						SR4						SR5					
Grid	01	02	03	04	05	06	01	02	03	04	05	06	01	02	03	04	05	06	01	02	03	04	05	06	01	02	03	04	05	06
Year 2023																														
acoustic							25						29						34											
UAS	22						25												38											
soil													29												42	42				
CT: Outdoor camera							25						26																	
Year 2024																														
acoustic	18	18	21				21	21	24				24	24	26															
point count / Merlin	19	19	21				21	21	24				24	24	27															
UAS	11	10	13					21							29				26						38	38	38			
soil			21	21	21		22	22				22																		
CT: Outdoor camera																				30						34				
Year 2025																														
acoustic	17	17	20				19	19	23				22	22	26															
point count / Merlin	17	17	20				20	20	23				22	22	26															
UAS		14	15					22	24											31	31					40	41			
soil									23	23	23		22	22				22												
CT: DIOPSIS														25	26					34						38				
CT: Insect Detect															29					34							38			
CT: Time Lapse													29	29	29				34	33	34				38	38	38			
Vegetation							19	19	23	23	23		22	22	26			22	34	34	34									

Table 2:
Device types and timing of use over three field seasons of work in BioMonitor4CAP based on growing degree-day (GDD) accumulations. SR = sampling round; UAS = uncrewed aerial system; CT = camera trap; CW = calendar week. Study site grids are color-coded based on elevation classification.

Tabelle 2:
Gerätetypen und Einsatzzeiten über drei Feldsaisons in BioMonitor4CAP basieren auf den wachsenden Gradtagakkumulationen (GDD). SR = Stichprobenrunde; UAS = unbemanntes Luftsystem; CT = Kamerafalle; CW = Kalenderwoche. Die Raster der Untersuchungsflächen sind farblich codiert basierend auf der Höhenklassifikation.

Elevation	Range (GDD)	End CW	End date
Low	0-300	25	18-Jun
	300-600	29	15-Jul
	600-900	33	12-Aug
	900-1200	37	13-Sep
	1200-1500	53	31-Dec
High	0-300	30	23-Jul
	300-600	38	17-Sep
	> 600	53	31-Dec

Grid 01 – Low-elevation selected research site

Grid 01 was established in summer 2023 near St. Veit an der Glan. Wooden posts were installed at four sampling points within a 5-ha parcel containing a young planting of wine grapes, experimental horticultural tree species, low-input grassland, and a small patch of riparian forest. Outdoor cameras (Ricoh WG-70, Ricoh Company, Ltd., Tokyo, Japan) were installed at two posts using an established approach for documenting flower-visiting insects [10]. The ICEB-SIENA team performed UAS missions over the grid at specific intervals. Soil samples for physicochemical analysis and for eDNA metabarcoding were taken from the four sampling points at two time periods: July and October. Acoustic recorders included Song Meter (Wildlife Acoustics, Inc., Maynard, MA, USA) series devices and AudioMoth (Open Acoustics Devices, Oxford, UK) devices that were installed on all four posts.

In 2024, drone flights were conducted, but they could not be performed in 2025 due to evolving local regulations. Soil sampling occurred at all sampling points in late May of both years, while Song Meter Micro and AudioMoth acoustic devices were installed in the spring at the four posts. Traditional point counting—performed by BirdLife Austria expert volunteers—was conducted to complement the technology-based monitoring solutions. The Merlin Bird ID app (Cornell Lab of Ornithology, Ithaca, NY, USA) recorded audio on a smartphone at precisely the same time as each point count for both seasons. Camera trapping for pollinator insects was not performed in 2024 due to a required change in device type, but in 2025, camera trapping was conducted using high-resolution time lapse construction cameras (TL3000, GD Digital Ltd., Shenzhen, China). Vegetation plots were established in 2025 to measure percent ground cover and functional species groups at specific time intervals.

Grid 02 – Low-elevation selected research site

Five sampling points were installed in October 2023 near Feldkirchen in Kärnten at the Metschach Outdoor Laboratory managed by ICEB [11]. Grid 02 is a former marsh that was drained around the turn of the 20th century and converted to agricultural land. In 1990, agricultural activities ceased, and the area was left to nature with management activities restricted to periodic mowing and vegetation monitoring. Due to the late-season grid establishment in 2023, only soil samples could be taken that year for physicochemical analysis and eDNA metabarcoding.

In 2024 and 2025, drone flights, soil sampling, bird monitoring, insect monitoring, and vegetation plot analysis were performed at Grid 02. For monitoring pollinator insects in 2025, construction cameras were installed at all sampling points. Additionally, two experimental camera trap setups were trialed. Insect Detect system modules [12] were installed at two sampling points alongside DIOPSIS sensors [13].

Grid 03 – High-elevation selected research site

In early spring 2024, Grid 03 was established near Ebene Reichenau using wooden posts at five sampling points. This site is located on a grassy slope ranging from 1,250-1,350 m elevation, with patches of coniferous forest. This 40-ha parcel is used primarily for hay and cattle production and has been managed by the same family for generations. A portion of the area is hand-scythed due to the steep topography, and another area is left with standing grass until late summer, promoting a highly diverse grassland plant community. In 2024 and 2025 the Grid 03 monitoring program closely paralleled the activities at Grid 01 and Grid 02, except that most activities began later due to climatic differences. In addition to soil sampling, acoustic monitoring, drone-based orthophoto collection, and vegetation plot assessment, in 2025 one Insect Detect system and one DIOPSIS sensor were installed at Grid 03, along with construction cameras at each of the five sampling points.

Grids 04-06 – Demonstration research sites

Demonstration research sites contained sampling points that were recorded using a high-precision global navigation satellite system device (Viva GS 16, Leica Geosystems AG, Heerbrugg, Switzerland), rather than marking with wooden posts. Grids 04 and 05 were established near Ebene Reichenau in spring 2024. Monitoring activities at these high-elevation demonstration grids were restricted to soil sample collection and analysis in 2024 and 2025, and vegetation plot documentation in 2025. Grid 04 is located within a heavily forested parcel on the north face of a steep slope. Three sampling points are established in clearings near the roadside, the fourth point located entirely within a closed forest and the fifth sampling point located in the middle of a field used for hay production. Grid 05 is located in a wide grassland that is bisected by a small river. One sampling point is located in a wet low-lying area of the field, while the other four points are located on ancient river terraces.

In 2024 Grid 06 was established following intensive consultation with the many landowners utilizing a large field near Maria Saal. This low-elevation grid most closely matches the intended project sampling point layout, with only slight deviations based on access restrictions. Grid 06 features nine sampling points where soil samples were collected in May 2024 and 2025. Vegetation plot documentation additionally occurred in 2025. Most sampling points are located in grassland habitats, with the remaining sampling points located at forest edges.

Biodiversity indicators, systems, programs, and policies

A background investigation of suitable agrobiodiversity indicators was performed early in the project. Project partners developed a framework for data collection and evaluation, including intensive research into the types of indicators that can be monitored effectively in the agricultural landscape. Project partners performed an exhaustive meta-analysis of more than 3,400 review papers covering the four indicator groups. A data storage platform was established, and a web-based interface was developed to provide visitors access to uploaded data. This interface will be managed until the conclusion of the project.

CUAS contribution: CUAS was involved in developing search terms for literature review in the fields of entomology, soil science, and remote sensing. We then provided independent assessment of journal articles for inclusion or exclusion in the final meta-analysis, a project deliverable [14]. With colleagues from Leibniz Institute for Agricultural Engineering and Bioeconomy, Potsdam, Germany, we published a methodology for how to perform a systematic review on the use of uncrewed aerial systems (UAS) in agrobiodiversity monitoring [15]. An additional article proposing new indicators for monitoring farmland biodiversity with connection to the Geo BON framework of Essential Biodiversity Variables was published [16]. These high-level outputs are targeted toward the scientific community and policy makers.

Socio-economic research

BioMonitor4CAP contains a thematic area on socio-economic research. Gathering rural stakeholder perceptions on agrobiodiversity monitoring is a key objective, where the values of agrobiodiversity data and monitoring techniques are assessed. Multiple formats of stakeholder involvement were offered. Thirty focus groups were assembled across six countries, where farmers and agricultural advisors from diverse production sectors shared their perspectives with a facilitator. Farming measures to promote biodiversity were discussed, as well as how the dimensions of environmental, economic, social, and personal well-being affected individual perspectives. In a next step, co-creation workshops took place, allowing policy makers and experts to develop policy recommendations.

To determine farmers' attitudes toward potential future changes to CAP subsidies, a discrete choice experiment (DCE) was conducted. Project partners developed a series of cards that were presented to farmers. Each DCE card indicated three hypothetical scenarios: one scenario where farmers would agree to a minor change to promote biodiversity on their farm for a small subsidy increase; one scenario where farmers would perform a major change for a large subsidy increase; and a third scenario where management would not change, but subsidies would not change either. Responses were statistically analyzed and reported in a peer-reviewed publication [16].

Lastly, to provide a framework for upscaling science-policy discussions, BioMonitor4CAP project partners gathered a comprehensive list of biodiversity observatories in Europe, with focus on those observatories that curate agriculturally-relevant information. Nearly 600 observatories were plotted on a web-based filterable map (https://www.biomonitor4cap.eu/en/project/agrobiodiversity-database) [17].

Austrian contribution: CUAS supported all socio-economic research tasks. We held five co-creation workshops, providing 10 farmers and 10 advisors the opportunity to share their perspectives on how the agroecosystem is linked to biodiversity. We held one co-creation workshop where eight advisors and policy makers came together to discuss the steps needed to improve agrobiodiversity literacy, including the successes and limitations of Austria's existing agrobiodiversity programs. We provided detailed contributions to a booklet on agroforestry [18], including translational assistance to release a German-language version. We co-authored the publication on the DCE surveys [16]. We further contributed a list of curated agrobiodiversity observatories from four European countries.

OUTLOOK AND CONCLUSION

BioMonitor4CAP project partners are currently performing data analytical steps to valorize the project findings. The goal of BioMonitor4CAP has been to develop evidence-based recommendations and case studies aimed at further harmonizing modern agriculture with habitat conservation, intended as part of a new CAP strategy. From the start, the project team was aware of the difficulty and complexity of these objectives, and despite the many complications and lessons learned, the research has advanced substantially.

In the project, ICEB has focused primarily on the topic of ecosystem monitoring and habitat protection in the agroecosystem. Trying to bring modern technologies to the farm level—and thereby to the operating farmers—was not always met with enthusiasm. However, our cooperators stood willing to engage in dialogue, a welcome finding considering the many voices that wanted to be heard in order to make a policy impact.

There will likely never be a one-size-fits-all set of measures that can be applied to all farms and agricultural areas across the EU. This was observed time and time again throughout the project. Every farm is subject to different influences and challenges, and many methods require further adaptation or are not applicable to specific situations. Furthermore, technologies continue to evolve. Many challenges that are outside of the scope of this project still stand in the way of a more comprehensive CAP strategy. What does emerge, however, is a path to jointly develop a strategy that equally satisfies the needs of consumers, policymakers, and farmers, thus promoting and preserving vital regional production in the long term through the circular economy and habitat conservation. ICEB and our project partners stand committed to aid with their expertise in this effort and to lay the ground work for further efforts and new research in sustainable agriculture.

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ABOUT THE AUTHORS

Daniel Dalton
UNESCO Chair on Sustainable Management of Conservation Areas
ICEB, CUAS
Villach, Austria
E-Mail: d.dalton@cuas.at

Vanessa Berger
UNESCO Chair on Sustainable Management of Conservation Areas
ICEB, CUAS
Villach, Austria

Jessica Fuchs
UNESCO Chair on Sustainable Management of Conservation Areas
ICEB, CUAS
Villach, Austria

Gernot Paulus
Spatial Informatics for ENvironmental Applications, ICEB
CUAS, Villach, Austria

Stefan Ruess
Spatial Informatics for ENvironmental Applications, ICEB
CUAS, Villach, Austria

Ulf Scherling
Spatial Informatics for ENvironmental Applications, ICEB
CUAS, Villach, Austria

Klaus Steinbauer
UNESCO Chair on Sustainable Management of Conservation Areas
ICEB, CUAS
Villach, Austria

Ilja Svetnik
UNESCO Chair on Sustainable Management of Conservation Areas
ICEB, CUAS
Villach, Austria

BACK TO CONTENT

Integrating remote sensing and in situ data to assess wetland ecosystem health within the Pressure-State-Response (PSR) framework in Lake Tana UNESCO Biosphere Reserve, Ethiopia

Daniel Ayalew Mengistu, Adrijana Car, Agumassie Genet Gela, Daniel Asfaw Bekele, Andargachew Abeje Derseh, Klaus Steinbauer, Michael Jungmeier

ABSTRACT

The Lake Tana Biosphere Reserve (LTBR) consists of wetlands that provide critical ecosystem services but face degradation from anthropogenic pressures and climate change. This study integrates the Pressure-State-Response framework with multi-temporal remote sensing (Landsat and Sentinel2, 2011–2025) and participatory citizen science. Landscape metrics (patch density, Shannon diversity index, net primary productivity) were derived alongside demographic and infrastructure layers to assess pressures. Quantitative data were triangulated with focus group discussions and participatory mapping. Results show that high population density (up to 13,000 individuals/km²) and cultivated land expansion (78% to 85% from 2011 to 2025) are primary degradation drivers, manifesting as landscape fragmentation and declining vegetation productivity especially in the eastern floodplain areas of LTBR. Integrating spatial analysis with local knowledge reveals spatially differentiated wetland vulnerability shaped by demographic, agricultural, and climatic factors. This approach demonstrates the feasibility of fusing objective spatial data with participatory evidence, offering a scalable model for evidencebased conservation policy in the LTBR and other sensitive wetland systems.

KEYWORDS

- *Lake Tana Biosphere Reserve*
- *PSR Framework*
- *Remote Sensing*
- *Citizen Science*
- *Landscape Metrics*

Integration von Fernerkundungs- und In-situ-Daten zur Bewertung der Ökosystemgesundheit von Feuchtgebieten im Rahmen des Pressure-State-Response-(PSR) Modells im UNESCO-Biosphärenreservat Tanasee, Äthiopien.

ZUSAMMENFASSUNG

Das Biosphärenreservat Tanasee (LTBR) besteht aus Feuchtgebieten, die kritische Ökosystemleistungen erbringen, jedoch durch anthropogene Belastungen und den Klimawandel degradiert werden. In dieser Studie wurde das Pressure-State-Response-(PSR) Modell mit multitemporaler Fernerkundung (Landsat und Sentinel-2, 2011–2025) und partizipativer Citizen Science angewandt und Landschaftsmetriken (Patch-Dichte, Shannon-Diversitätsindex, Nettoprimärproduktion) wurden zusammen mit demografischen und infrastrukturellen Ebenen abgeleitet, um Belastungen zu bewerten. Quantitative Daten wurden mit Fokusgruppendiskussionen und partizipativer Kartierung erhoben. Die Ergebnisse zeigen, dass hohe Bevölkerungsdichten (bis zu 13.000 Personen/km²) und die Ausweitung von Ackerland (von 78 % auf 85 % zwischen 2011 und 2025) die primären Treiber der Degradation sind, die sich in Landschaftsfragmentierung und abnehmender Vegetationsproduktivität insbesondere in den östlichen Auenbereichen des LTBR äußern. Die Verknüpfung räumlicher Analysen mit lokalem Wissen macht eine räumlich differenzierte Vulnerabilität der Feuchtgebiete sichtbar, die durch demografische, landwirtschaftliche und klimatische Faktoren geprägt ist. Dieser Ansatz zeigt die Machbarkeit der Verschmelzung objektiver räumlicher Daten mit partizipativ erhobenen Evidenzen und bietet ein skalierbares Modell für evidenzbasierte Naturschutzpolitik im LTBR und in anderen empfindlichen Feuchtgebietssystemen.

INTRODUCTION

Wetlands are among the most biodiverse and valuable ecosystems, providing water purification, groundwater recharge, flood control, habitat for endangered species, and socio-economic benefits. Despite their importance, they face rapid degradation worldwide due to anthropogenic pressures like population growth, land-use conversion, and lack of monitoring [1].

UNESCO Biosphere Reserves are designed as pockets of hope for local solutions to global challenges [2]. The Lake Tana Biosphere Reserve (LTBR), designated in 2015, lies within the Eastern Afromontane Biodiversity Hotspot and contains Ethiopia's largest lake. Lake Tana is the source of the Blue Nile and hosts ecologically critical wetlands [3]. However, these wetlands face invasion by water hyacinth (*Eichhornia crassipes*), sedimentation, land-use changes, and a cultural perception of wetlands as "wastelands" that drives drainage for agriculture. Weak institutional monitoring and limited community engagement compound the problem.

To bridge policy and ecological realities, the *ComWet* project (funded by Africa UniNet project number P-144 Ethiopia) develops a participatory wetland health assessment, building on the prior *CoMon* project and aligning with Ramsar conservation goals, Ethiopian EPA regulations, and SDGs 13, 14, and 15. *ComWet* integrates citizen science approaches of focus groups, community mapping, and expert interviews with advanced geospatial technology. The current report applies an adapted Pressure-State-Response (PSR) framework (derived from the DPSIR model that also includes Drivers and Impacts) to assess LTBR wetland health. The PSR framework links socio-economic drivers (Pressures) to ecological changes (State) and management actions (Response), creating a clear cause-and-effect narrative. By synthesizing multi-temporal remote sensing with participatory data, this study aims to provide actionable evidence for LTBR management and long-term ecological monitoring.

METHODS

Description of the study area

The LTBR is located in northwestern Ethiopia (11°25′07″N–12°29′18″N, 36°54′01″E–37°47′20″E) (Figure 1), covering 695,885 ha. The size of the core area measures 22,841 ha (7,699 ha terrestrial); buffer area measures 187,567 ha (30,969 ha terrestrial); and transition area measures 485,477 ha (354,297 ha terrestrial). The region hosts some of the largest and most ecologically significant wetlands in Ethiopia and the Horn of Africa, along with important fish resources (67+ species, 70% endemic). Designated by UNESCO in June 2015, the LTBR contains Lake Tana, Ethiopia's largest highland freshwater lake and the main source of the Blue Nile, providing critical ecosystem services. It lies within the Eastern Afromontane Biodiversity Hotspot and includes four terrestrial and three freshwater Key

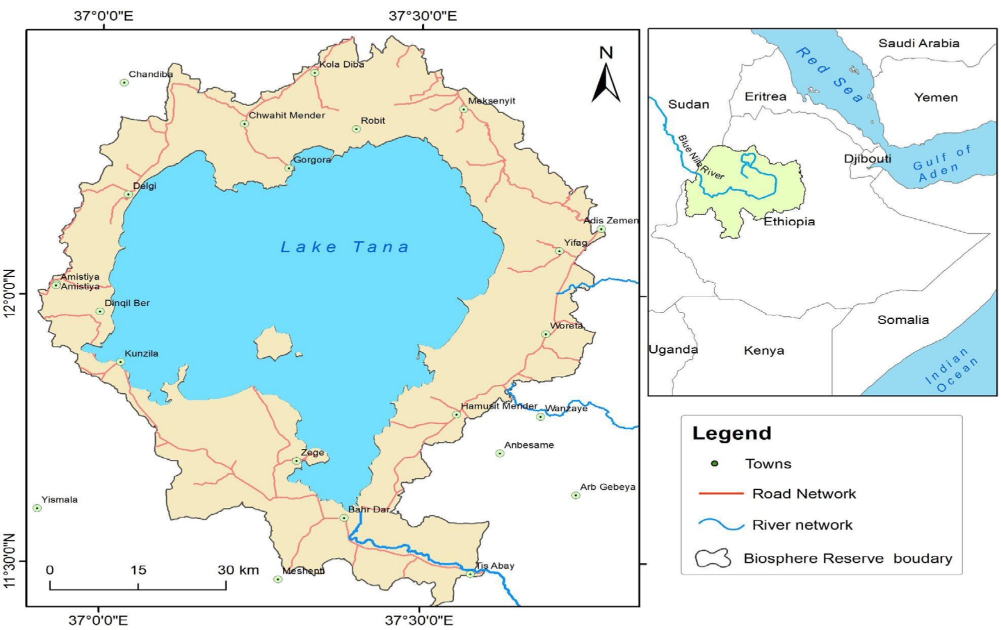

Fig. 1

Figure 1: Map of the ComWet project area. (Source: ComWet project)

Abbildung 1: *Karte des ComWetProjektgebiets. (Quelle: Projekt ComWet)*

Biodiversity Areas. It is recognized as an Important Bird Area and is of global significance for agricultural genetic diversity. Culturally, the reserve preserves unique Ethiopian Orthodox Tewahedo Church monasteries and churches, some dating to the 13th century, containing valuable Christian treasures [4].

Dataset type and sources

A comprehensive dataset array was compiled for wetland health assessment. Socioeconomic data (population density, urbanization) came from the national census [5]. Road network data from *OpenStreetMap*, verified by local records, assessed infrastructure impacts (fragmentation, areal shrinkage, pollution, biodiversity loss) [6]. Core spatial analysis used multitemporal Landsat and Sentinel2 imagery from USGS Earth Explorer [7] and Copernicus Data Space [8]. Landscape metrics were calculated using LecoS (QGIS) and FRAGSTATS [9], [10], including:

- **Patch Density (PD):** *patches per unit area; high values indicate fragmentation reducing habitat quality.*
- **Patch Richness (PR):** *diversity of patch types;* high values signal fragmentation.
- **Shannon Diversity Index (SHDI):** *diversity based on number and abundance of land cover types.*
- **Contagion Index:** *patch aggregation; high values* show contiguous stable wetlands; low values show scattered patches disrupting ecological processes.
- **Largest Patch Index (LPI):** *proportional size of dominant wetland patch;* low values signal habitat loss.

DATA ANALYSIS

To assess State and Pressures under the PSR model, we used Landsat series (5 TM, 8 OLI/TIRS, 9 OLI2) across three periods: pre-2015 (baseline), post-2015, and 2025. All images underwent radiometric calibration, atmospheric correction, and registration. Supervised classification, spectral indices (e.g., normalized difference vegetation index, NDVI), and land use-land cover (LULC) change analysis identified wetland loss, fragmentation, and hydrological alteration, with GPS field observations for groundtruthing.

To contextualize remote sensing and address PSR, a citizen science approach integrated local and institutional knowledge [11]. Methods included focus group discussions (FGDs) with community representatives, participatory community mapping (boundaries, degradation hotspots), and semistructured interviews with experts and local knowledge holders. This participatory layer grounds the research in local reality, validates spatial analysis, and strengthens proposed management responses.

By employing the PSR framework, remote sensing and participatory methods were iteratively integrated. Remote sensing provided spatiotemporal evidence of pressures, state, and responses; participatory methods explained underlying drivers, validated changes, elaborated impacts, and identified responses. The PSR framework synthesized these into a cause-and-effect narrative. Analysis combined quantitative (statistical analysis of remote sensing data) and qualitative (thematic analysis of FGD/interview transcripts) techniques, with triangulation, strengthening findings.

Tab. 1

Criteria	Indicator	Description	Data Source
Pressure	Population density	Inhabitants per km^2	[5]
	Cultivated area	Percentage of cultivated area per unit area	[7], [8]
	Proximity to road	Distance from road	[6]
	Urbanization rate	Percentage of urban population per unit area	Central Statistical Agency (CSA) & Land Use Land Cover (LULC)
State	PR	Number of patches	[7], [8]
	NPP	Net Primary Productivity	
	Average annual rainfall	Mean rainfall	Station data (Ethiopian Meteorological Institute, EMI)
	PD	Wetland area is divided by the provincial area	[8], [9]
	LPI	Largest patch area divided by total landscape area	
	SHDI	Proportion of patch type with in province area	
	Water quality	Water quality tests	In situ measurement
	Slope (°)	Angle of terrain (°)	[7]
Response	Wetland degradation rate	Percentage of wetland area loss within the province area	[7], [8]
	ESV	Ecosystem service value in US$ per ha per year	[7], [8]

Table 1: *Identified indicators and their description and source for wetland ecosystem health assessment.*

Tabelle 1: *Identifizierte Indikatoren sowie deren Beschreibung und Quellen für die Bewertung der Gesundheit von Feuchtgebiets-Ökosystemen*

RESULTS & DISCUSSION

This study systematically identified and computed a set of indicators capturing the complex interactions between human pressures, ecological states, and management responses affecting wetland health in LTBR. Integrating remote sensing metrics with participatory insights from local communities provides a comprehensive picture of how pressures translate into ecological change, enabling targeted conservation strategies.

Following the PSR framework, pressure indicators represent human activities that stress the environment (Figure 2) [12]. In the LTBR, population density ranges from 0 to 13,000 inhabitants per km^2, with highest concentrations in Fogera, Libo Kemkem, Dembia, Gondar Zuria, and Bahir Dar. These dense areas intensify wetland conversion to agriculture, settlements, and infrastructure, a trend confirmed by previous studies linking flood recession agriculture and settlement expansion to degradation [13], [14]. Cultivated land dominates the reserve, and its expansion into wetlands alters hydrology, reduces vegetation, and increases nutrient runoff. Fertile floodplains like Fogera are more than 75% cultivated [1], [14], fragmenting wetlands and reducing their buffering capacity. Citizen mapping further validates these trends, revealing annual dry season drainage campaigns led by development agents, reflecting the local perception of wetlands as "wastelands." Globally, wetland conversion to agriculture is recognized as a leading cause of degradation [15]. Infrastructure development adds another pressure layer: road networks intersect wetland clusters in Fogera, Bahir Dar, and Bahir Dar Zuria, creating fragmentation, pollution, and hydrological disruption that facilitate settlement expansion

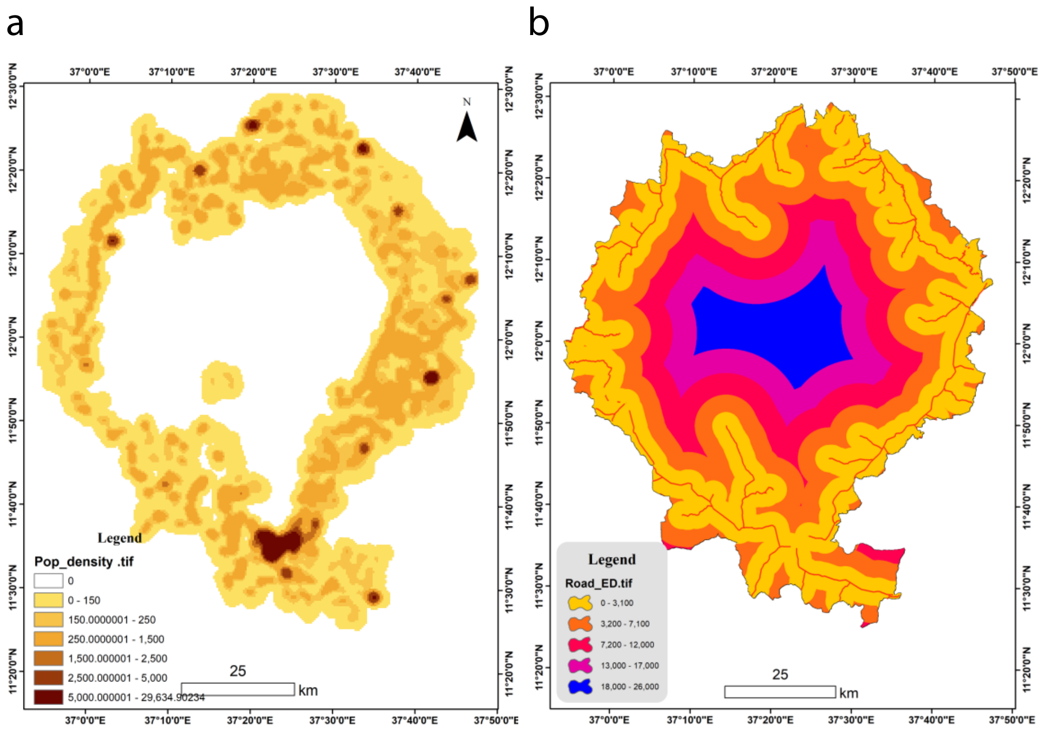

Fig. 2

Figure 2: Population density (a), Road network (b). (Source: ComWet project)

Abbildung 2: *Bevölkerungsdichte (a), Straßennetz (b). (Quelle: Projekt ComWet)*

and land conversion [16]. Urban expansion around Bahir Dar and other settlements has also accelerated, reflecting how socioeconomic development trajectories intersect with ecological vulnerability.

State indicators describe environmental conditions changed by pressure impacts (Figure 3) [12], [17]. Net Primary Productivity (NPP), derived from NDVI, is a key measure of ecosystem function [18], [19]. Most of the LTBR exhibits low productivity (<5 g/m²), while approximately 667 km² experience moderate productivity (10–20 g/m²); areas with high productivity (>20 g/m²) are negligible. Moderate NPP values are concentrated in the eastern floodplain, northern Dembia, North Achefer along the Gilgel Abbay, and smaller pockets in Bahir Dar Zuria, corresponding to intensified cultivation and settlement expansion. Widespread low values signal reduced vegetation resilience and potential degradation. Rainfall distribution, derived from over 25 years of meteorological records, shows a mean annual range of 850–1500 mm. Southern districts including Dera, Bahir Dar Zuria, Dangla, and Alefa receive relatively higher rainfall, while most of the reserve experiences totals below 1200 mm. Wetter zones sustain hydrological connectivity but risk flooding, sediment deposition, and nutrient loading; rainfall-deficient areas face water shortages, reduced soil moisture, and wetland contraction. When coupled with population pressure and agricultural expansion, rainfall variability intensifies ecological stress [17], [20].

Landscape fragmentation metrics further illustrate ecosystem state: PD covers ~270 km² (including protected and church forests), with high values indicating fragmentation and edge effects [21]. PR and landscape diversity indices reveal increasing cropland and settlement patches. Water quality, another state indicator, declines near settlements and cultivated areas due to nutrient loading, turbidity, and eutrophication [22]. Together, these state indicators demonstrate that LTBR wetlands are characterized by low vegetation productivity, uneven rainfall distribution, increasing fragmentation, declining water quality, and terraindriven vulnerability, directly linking socioeconomic drivers to physical and biological degradation.

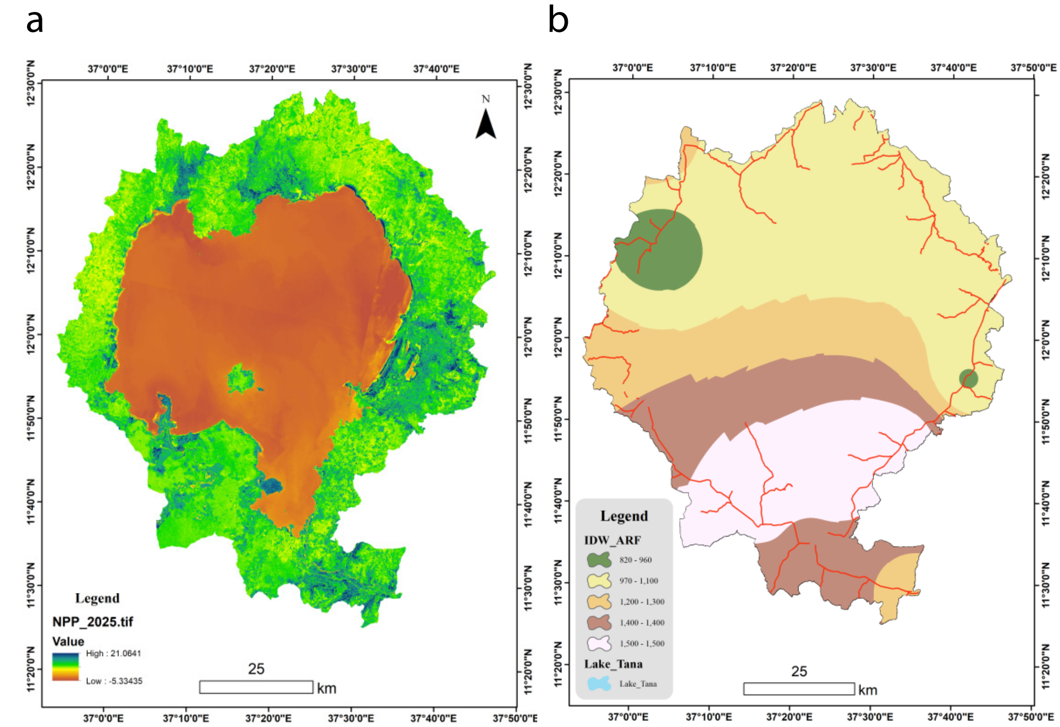

Fig. 3

Figure 3: Net Primary Productivity (NPP) in 2025 (a); Annual rainfall distribution in the LTBR area (b). (Source: ComWet project)

Abbildung 3: *Nettoprimärproduktion (NPP) im Jahr 2025 (a); jährliche Niederschlagsverteilung im LTBRGebiet (b). (Quelle: Projekt ComWet)*

Response indicators in this study reflect the manifested consequences of pressures and states, expressed as degree of wetland degradation and loss of ecosystem service values [12], [23]. In the LTBR, wetlands are distributed unevenly, with the majority concentrated in the eastern Fogera floodplain (Fogera and LiboKemkem districts), additional clusters in the south and southwest along the Gilgel Abbay River in Achefer District, and in the north along the Megech River in Dembia District (Figure 4) [13], [24]. The eastern floodplain features high population density and moderate NPP, reflecting intensive cultivation and settlement expansion. These spatial contrasts illustrate that wetland degradation is not uniform but context-specific, driven by the interaction of climatic variability and human activity. As wetlands fragment and lose ecological integrity, their capacity to provide

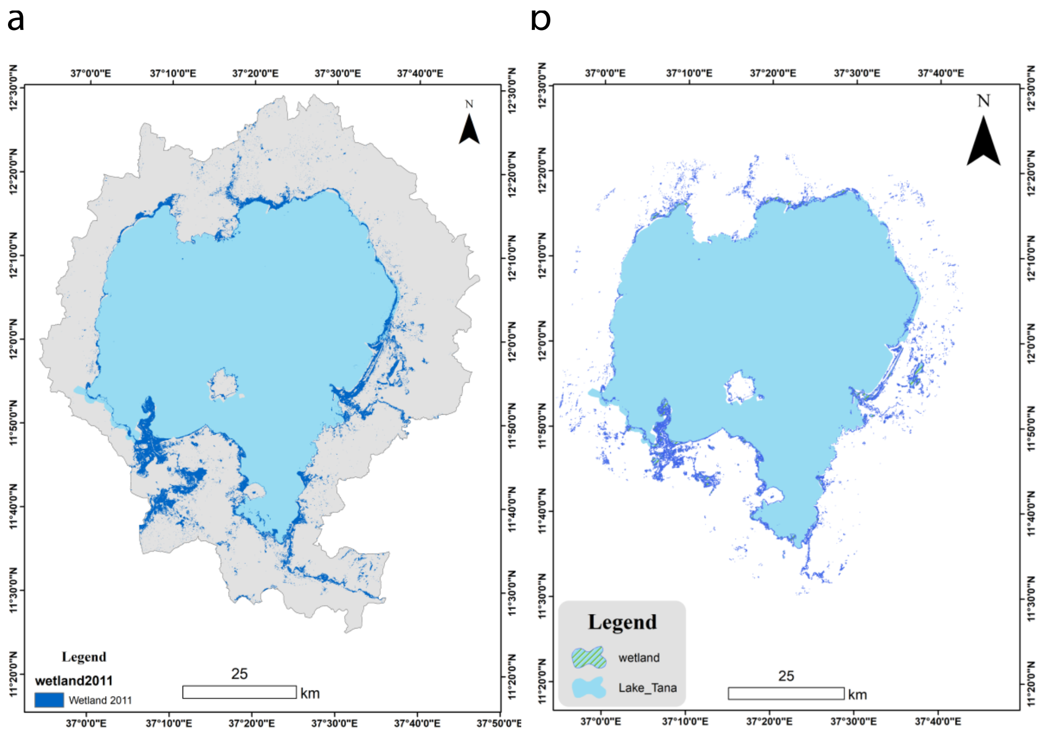

Fig. 4

Figure 4: Wetland distribution derived from the Landsat imagery In 2011 (a); in 2025 (b). (Source: ComWet project)

Abbildung 4: *Verteilung der Feuchtgebiete, abgeleitet aus LandsatBilddaten, 2011 (a); 2025 (b). (Quelle: Projekt Com Wet)* ecosystem services—including water flow regulation, biodiversity support, fisheries, grazing land, and flood buffering—declines, undermining both ecological sustainability and local livelihoods.

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ABOUT THE AUTHORS

Daniel Ayalew Mengistu
Geospatial Data and Technology Center (GDTC), Bahir Dar University, Bahir Dar, Ethiopia

Adrijana Car
Faculty of Engineering & IT, CUAS Villach, Austria

Agumassie Genet Gela
GDTC
Bahir Dar University
Bahir Dar, Ethiopia

Daniel Asfaw Bekele
GDTC, Bahir Dar University
Bahir Dar, Ethiopia
E-Mail: Daniel.Asfaw@bdu.edu.et

Andargachew Abeje
Derseh, GDTC
Bahir Dar University
Bahir Dar, Ethiopia

Klaus Steinbauer
UNESCO Chair on Sustainable Management of Conservation Areas
ICEB, CUAS
Villach, Austria

Michael Jungmeier
UNESCO Chair on Sustainable Management of Conservation Areas
ICEB, CUAS
Villach, Austria

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Book Reviews

All about grasshoppers: "Kärntens Heuschrecken" in focus

Klaus Steinbauer

ABOUT THE EDITOR AND AUTHORS

The authors of "Kärntens Heuschrecken"—translated Grasshoppers of Carinthia—display decades of expertise and are outstanding experts of this species group. The author team is composed of Günther Wöss, Lisa Liska, Christine Berg, Franz Essl, and Thomas Zuna-Kratky, all biodiversity experts in zoology and ecology with years of practical experience in the field and taxonomic experience in the museum. Many years of invaluable knowledge about this interesting species group was packed into a single publication, which itself serves as a profound baseline of current knowledge for grasshopper species in Carinthia. Their enthusiasm is present throughout the book and can be felt on every page. The editor Andreas Kleewein, head of Bird Life Carinthia, is a Carinthia-based zoologist himself, and shares a broad interest in different species group as well as practical experiences in zoological field surveys. Together, the editor and authors of Heuschrecken Kärntens have produced a magnificent status quo on the current knowledge of presence, distribution and threats facing Carinthian grasshoppers, an urgently needed example for biodiversity research in a changing world.

CONTENT AND STRUCTURE

Overall, Kärntens Heuschrecken is not a simple catalogue of grasshopper species found in Carinthia. Rather, it functions as an entire compendium. The book is divided into three main chapters: a general chapter providing an overview on grasshopper biology, a chapter on distinct species, and a special chapter on grasshopper biodiversity.

The authors provide a thorough introductory chapter that reviews the history of research, characterizes grasshopper habitats with their conservation status, and assesses threats to Carinthian grasshoppers. A dedicated subchapter on general grasshopper anatomy highlights the key morphological distinctions required for identification and directly supports the subsequent identification key. The key includes not only species currently present in Carinthia but also those likely to be found there in the future. The identification key is also available via QR code, facilitating use during fieldwork and excursions. In addition, the book provides a checklist of all 95 grasshopper species recorded at least once in Carinthia (87 of which are currently present), together with their respective Red List statuses.

Following the general chapter, the main species chapter presents carefully structured profiles for each species. These include a detailed distribution map within Carinthia and ecologically relevant information on month of occurrence, elevation, and habitat for each detection. For stridulating species, a QR code is provided, linking to species-specific acoustic recordings accessible via smartphone. A historical citation is provided for most species, reflecting the enthusiasm shared by earlier naturalists and the present authors. Each profile is complemented by a high-quality photograph of the species and images of typical habitats, yielding a comprehensive species-level overview.

The third, special chapter offers more detailed information on grasshopper diversity hotspots in Carinthia and includes an annotated catalog of type specimens first described from Carinthia. It presents several anecdotes and accounts of Carinthia's cryptic, endemic, and newcoming grasshopper species.

RELEVANCE FOR THE FIELD OF NATURE CONSERVATION

By assembling the current state of knowledge on the distribution of grasshoppers in Carinthia, Kärntens Heuschrecken represents a resource of high relevance for nature conservation. In particular, the checklist with conservation status for each species and the subchapter on grasshopper diversity hotspots underscore the book's value for practitioners and researchers. Because the material is presented in an illustrative and accessible way, the book also serves laypersons and students well, providing a strong entry point into conservation-oriented work on Orthoptera in Carinthia.

CONCLUSION

"Kärntens Heuschrecken" is highly recommended for readers interested in biology and nature conservation, particularly those drawn to an organism group that is observable both visually and acoustically in everyday environments. The volume serves as a valuable reference, with subchapters spanning historical context, anatomy, identification, conservation status, habitats, and species profiles, as well as engaging anecdotes. Its careful synthesis of highquality photographs, diagnostic illustrations, and welldocumented facts makes it useful to both specialists and nonspecialists and provides a comprehensive overview of Carinthia's grasshopper fauna.

Notably, the book's QR codeenabled access to speciesspecific sounds and the identification key increases its practicality in the field, while species accounts are strengthened by detailed distribution maps and ecological information. The inclusion of a complete checklist with Red List categories, an assessment of diversity hotspots, and an annotated catalog of type specimens further enhances its scientific and conservation value. Transparent reporting of data collection and processing bolsters credibility and makes the work a reliable baseline for future monitoring.

Taken together, "Kärntens Heuschrecken" functions as both a compendium and a field guide—especially by using the digital supplements—equally relevant to researchers, practitioners, educators, students, and engaged naturalists.—equally relevant to researchers, practitioners, educators, students, and engaged naturalists.

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ABOUT THE AUTHOR

Dr. Klaus Steinbauer
UNESCO Chair on Sustainable Management of Conservation Areas
ICEB, CUAS
Villach, Austria
E-Mail: k.steinbauer@cuas.at

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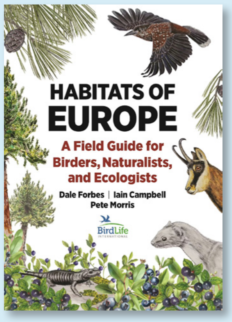
Exploring Europe’s ecological diversity: *Habitats of Europe*

Polona Zakrajšek



The book *Habitats of Europe: A Field Guide for Birders, Naturalists, and Ecologists*, authored by Dale Forbes, Iain Campbell, and Pete Morris, was published by Princeton University Press in 2026 and presents a comprehensive overview of Europe’s diverse ecological landscapes [1]. This 432-page contribution is part of the “Habitats of the World” series, which comprises seven continental books and one global volume. The global book describes 189 generalized habitats, while the seven continental books dive deeper, with a total of 545 habitats across the volumes. *Habitats of Europe* presents 56 habitats in total, covering the following biomes: conifer forests, deserts, temperate broadleaf woodlands, savannas, grasslands and steppes, Mediterranean shrublands, tundra, freshwater habitats, saline habitats, and anthropogenic habitats.

The book serves both as a practical field guide and as a reference for understanding Europe’s habitats and the biodiversity they support. It explains the various functions of habitats and how they have developed, where they are found across the continent, and how they support groups of characteristic species. Each habitat is set out in a clear format that combines short ecological notes with visual aids, making it easy to use in the field or at home. Across the book there are 465 color photographs, 52 illustrations, 70 diagrams, and 43 maps, all helping you match what you read with what you see. A key strength is the two-way link between habitats and species: if you can recognize the habitat, you can look for its typical wildlife, and if you know the wildlife you can often read the habitat from it. The text reads like a nature documentary in print, with poetic, emotionally resonant language that stays scientifically accurate.

The first part of the book introduces core concepts that help the reader understand the context and relationships within European habitats. This includes habitat boundary types and ecotones, the Köppen climate classification system, biomes, and useful habitat-related terminology. The regions of Europe are then presented with generalized habitat niche diagrams, illustrating the sequences of major zonal habitat development—following influences of precipitation, temperature, and fire regimes. The descriptions also include anthropogenically dominated habitats, such as European cropland and European urban environments, which are widespread in some regions.

The main part of the book follows the structure of each biome and its habitats. Each is presented with sections that include a brief description, affinities to other global and continental habitats, distinctive plant species, a range map and distribution, and the key biotic and abiotic characteristics. The wildlife section sparks curiosity, making clear links between vegetation and animals. The species are predominantly birds; however, mammals, amphibians, and other vertebrates are also included. Additional information is provided about where such habitats can be observed (e.g., specific protected areas), accompanied by photographs and other graphical materials about each habitat and its associated wildlife.

The book is accompanied by an open-access website (www.habitatsoftheworld.org). Its goal is to provide an overview of world habitats, allowing the reader to search via birds or habitats to understand their relationships globally. At the time of writing, that search function is not yet available. However, it does provide an overview of the contents of other published books and offers additional services, such as booking birding tours worldwide.

At a cost of about 38 €, the book is an accessible resource for students, nature guides, and protected area staff as an environmental education aid, and for engaged amateurs as a field guide. It is an interesting and educational read from start to finish, and can be used as a tool to easily recognize habitats and their species while in the field or an unfamiliar environment. The book is an inviting gateway to habitat-level thinking and curiosity about the wildlife all around us.

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ABOUT THE AUTHOR

Polona Zakrajšek
UNESCO Chair on Sustainable Management of Conservation Areas
ICEB, CUAS
Villach, Austria
E-Mail: p.zakrajsek@cuas.at

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Carinthia Nature Tech
Author Guidelines

Revised 2/4/2025

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The journal Carinthia Nature Tech is organized into key sections: 1) Preface, 2) Scientific Articles: *Full Articles*, 3) Scientific Articles: *Short Articles*, 4) *Short Notes*, 5) *Book Reviews*. Two issues of Carinthia Nature Tech will be published annually. Only previously unpublished articles may be accepted. The editors may propose changes to the text based on feedback from the reviewers. Alterations will be discussed with the authors. Carinthia Nature Tech will use third party tools to check submitted texts for plagiarism. Plagiarism reports will be kept as part of the documentation process of the paper submission. Any detection of plagiarism will lead to an immediate rejection of the submission.

The articles must have a clear connection to the Alps-Adriatic Region. At least one contributing author or the study area must be directly connected to the region. The connection to the area must be clear through linking author affiliations or study locations to Carinthia. The Editorial Office will verify this connection at the time of manuscript submission.

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Graphics should be submitted as .png, .jpg, or .tiff formats, or embedded in .doc, .docx formats. Images should be provided in high quality resolution (300 dpi or greater). Videos should be provided as .mp4 files. Diagrams should be submitted as .xlsx. Supplementary materials should be accessible in a commonly used file type.

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The *Book Reviews* section is intended to evaluate new stand-alone publications in the field of technologies in nature conservation and with a connection to the Alps-Adriatic Region. Each book review should be 3,500 – 8,000 characters long, including spaces, with a German-language abstract of 200 – 500 characters, including spaces. It should include summarizing information identifying authors and editors, title of the book, year published, the name of the publisher, and a link or reference to the original source. The review should provide a brief summary of the book. Critical analysis of the strengths and weaknesses of the book, comparison to other works in its field, and its overall relevance for the intended audience should be prominent in the review. *Book Reviews* will be managed within the editorial office and evaluated by the Editorial Office. *Book Reviews* will not be indexed and will not receive DOIs.