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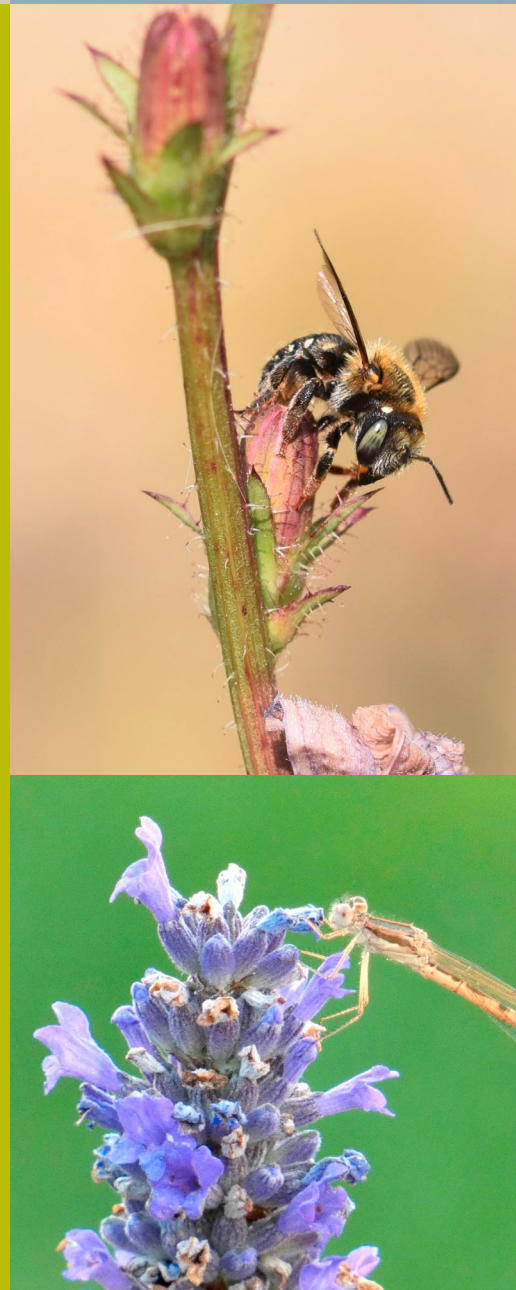
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Acta ZooBot Austria

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**Biodiversität
im Diskurs von
Wissenschaft und
Gesellschaft**

Acta ZooBot Austria

Band 162

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Titelseite:

Weißfleckige Wollbiene *Anthidium punctatum* auf einer Knospe der Gemeinen Wegwarte *Cichorium intybus*. Foto: J. Hackl | *Anthidium punctatum* on a bud of common chicory *Cichorium intybus*. Photo: J. Hackl

Ein sehr junges Weibchen der Gemeinen Winterlibelle *Sympecma fusca* auf Lavendel-Blüte *Lavandula angustifolia*. Foto: A. Chovanec | A very young female of common winter damselfly *Sympecma fusca* on a lavender flower *Lavandula angustifolia*. Photo: A. Chovanec

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Aufbau einer Malaisefalle zur Erfassung von Arthropoden unterhalb des Sonnblick-Observatoriums, Nationalpark Hohe Tauern. Foto: Sarah M. Wagner | Setup of malaise trap to sample arthropods below the Sonnblick Observatory, Hohe Tauern National Park. Photo: Sarah M. Wagner

Strukturreicher Naturgarten mit Ruderalvegetation, Trockensteinmauer, Totholzangebot und vielfältigen Nisthilfen für Insekten. Foto: J. Hackl | A structurally rich natural garden featuring ruderal vegetation, a dry stone wall, deadwood and a variety of nesting aids for insects. Photo: J. Hackl

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Vorwort

Eines der herausragendsten Merkmale der belebten Natur ist Ihre Vielfalt. Wir leben in einer Zeit, in der diese Biodiversität multiplen Gefahren ausgesetzt ist. Das Bewusstsein zu schaffen, welche unglaublichen Verluste der Natur drohen und was auch wir Menschen dabei riskieren, ist ein dringender Auftrag. Biodiversitätswissenschaften und Biodiversitätsforschung beschäftigen sich auf lokaler wie globaler Ebene mit der Analyse der Gefahren und kommen unweigerlich zum Schluss, dass menschliche Aktivitäten zu den Hauptursachen dieser negativen Entwicklung zählen.

Für die Zeitschrift *Acta ZooBot Austria* ist Biodiversität immer schon ein zentrales Thema. Von taxonomischen, faunistischen, ökologischen und biohistorischen Fragestellungen in den allgemeinen Beiträgen, über Schwerpunktbände zu Schutzgebieten, Biologie-Didaktik oder Biodiversitätstagungen ist es uns ein großes Anliegen, das Thema Biodiversität aus den unterschiedlichsten Blickwinkeln zu beleuchten.

Der vorliegende Band enthält eine Reihe von Beiträgen, die bei den „Tagen der Biodiversität 2025“ an der Universität für Bodenkultur in Wien (25.–28. Februar 2025) präsentiert wurden. Die Palette reicht von normativ-rechtlichen Aspekten bis zu Faunenerhebungen, von Biodiversitätsbildung und -plattformen bis zu Schutzmaßnahmen und gesellschaftspolitischen sowie künstlerischen Auseinandersetzungen mit dem Thema. Auch die „Allgemeinen Beiträge“ des vorliegenden Bandes, die sich nicht auf die „Tage der Biodiversität 2025“ beziehen, behandeln Fragen der Biodiversität.

Wir danken daher den Organisator:innen der Biodiversitätstage, dass sie die Vortragenden motiviert haben, ihre Beiträge in der *Acta ZooBot Austria* zu publizieren. Wir danken den Autorinnen und Autoren für ihre interessanten Artikel und den Gutachterinnen und Gutachtern für die Sicherstellung der Qualität der Beiträge in unserer Zeitschrift. Wir alle haben mit diesen gemeinsamen Anstrengungen einen wertvollen Beitrag zum Verständnis der Biodiversität und ihrer Bedeutung geleistet.

Editorial

One of the most remarkable features of the living world is its diversity. We live in an age in which this biodiversity is exposed to multiple threats. Raising awareness of the incredible losses that nature faces, and what we humans stand to lose as a result, is an urgent task. Biodiversity sciences and biodiversity research analyse these threats at both local and global levels and inevitably conclude that human activities are among the main causes of this negative trend.

For the journal *Acta ZooBot Austria*, biodiversity has always been a central theme. From taxonomic, faunistic, ecological and biohistorical issues in the general articles, through to special issues on protected areas, biology education or biodiversity conferences, our aim is to shed light on the topic of biodiversity from a wide variety of perspectives.

This volume contains a series of papers presented at the ‘Biodiversity Days 2025’ at the University of Natural Resources and Life Sciences, Vienna (25.–28. February 2025). The topics range from normative and legal aspects to faunal surveys, from biodiversity education and platforms to conservation measures as well as socio-political and artistic engagements with the subject. The ‘general articles’ in this volume, which do not relate to the ‘Biodiversity Days 2025’, also address issues of biodiversity.

We would therefore like to thank the organisers of the Biodiversity Days for encouraging the speakers to publish their papers in *Acta ZooBot Austria*. We thank the authors for their interesting articles and the reviewers for ensuring the quality of the contributions in our journal. Through these joint efforts, we have all made a valuable contribution to the understanding of biodiversity and its significance.

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Tage der Biodiversität 2025 | Biodiversity Days 2025

25–28 February 2025

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<https://biodiversitaetstage.boku.ac.at/>

Die Biodiversitätsforschung braucht mehr Partnerschaften

Katrin Vohland ¹

In diesem Artikel werden verschiedene Trends in der Biodiversitätsforschung analysiert und deren Bedeutung für ihre zukünftige Entwicklung diskutiert. Als wesentliche Trends werden die digitale Zugänglichkeit von Daten – und damit verbunden ein erweitertes Methodenspektrum, gesellschaftliche und globale Debatten um koloniale und andere Gerechtigkeitsfragen – sowie die zunehmende Integration von Biodiversitätsthemen in die Wirtschaftsforschung beschrieben. Angesichts jedoch weiterhin mangelnder Effektivität der Forschung im Hinblick auf die normativen Ziele des Abkommens zur Biologischen Vielfalt (CBD) werden mögliche Partnerschaften mit Akteuren aus Wirtschaft und Gesellschaft skizziert, um diese Ziele zu erreichen. Dabei geht es nicht nur um inhaltliche Abstimmungen, sondern auch um die Organisation von zielführenden partizipativen Prozessen.

Vohland K (2026) Biodiversity research needs more partnerships

This article analyses various trends in biodiversity research and discusses their significance for its future development. The main trends described are the digital accessibility of data and the associated expansion of the range of methods, social and global debates on colonial and other justice issues, and the increasing integration of biodiversity issues into economic research. However, given the continuing lack of effectiveness of research with regard to the normative goals of the Convention on Biological Diversity (CBD), possible partnerships with actors from business and society to achieve these goals are outlined. This involves not only coordinating content, but also organising goal-oriented participatory processes.

Keywords: biodiversity, digital transformation, big data, colonialism, transdisciplinarity, green bonds, science-policy interface, citizen science.

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Einleitung

Eine Session auf den österreichischen Biodiversitätstagen im Februar 2025 trug den Namen „Zwischen Dokumentation und High-Impact: Die Zukunft der Biodiversitätsforschung in Österreich“ und machte erstmal stutzig: Schließen sich Dokumentation und High-Impact aus? Ist mit Dokumentation das Monitoring von Arten, ja oft in Kooperation mit Bürgerinnen und Bürgern Citizen Science genannt, und ist mit High-Impact gemeint, in Science, Nature und PNAS zu publizieren? Oder bezieht sich Impact auf gesellschaftlichen Impact, auf Wirksamkeit? Diese Art von Wirksamkeit bezogen auf Gesellschaft und ihre Umwelt wird allerdings eher selten sprachlich mit *High-Impact* assoziiert.

Und was hat es mit dem Zukunftsbegriff auf sich. Ist er analytisch gemeint? Welche Trends in der Biodiversitätsforschung beobachten wir und wie können wir darauf reagieren? Oder betrachten wir die Biodiversitätsforschung normativ, wie und mit wem wollen wir sie in der und für die Zukunft gestalten?

Und „in Österreich“ ist auch ein relevanter Aspekt. Österreich verfügt über mehr Naturräume auf kleiner Fläche als viele andere Länder und weist mit dem Biodiversity Hub Österreich¹ ein Akteursnetzwerk über verschiedene Einrichtungsformen auf. Viele generelle Herausforderungen und Trends der Biodiversitätsforschung scheinen allerdings global und nicht spezifisch für Österreich.

Der Beitrag gliedert sich (1) in die Analyse von aktuellen Trends in der Biodiversitätsforschung und ihre Extrapolation in die Zukunft sowie (2) unsere eigenen Gestaltungsmöglichkeiten in diesem Feld. Unter der Annahme, dass sich die Biodiversitätsforschung an den normativ positiv besetzten Zielen des Abkommen zur Biologischen Vielfalt orientiert – Biologische Vielfalt schützen, nachhaltig nutzen und globale Gerechtigkeitsaspekte implementieren – werden zudem Optionen diskutiert, Biodiversitätsforschung ohne die Aufgabe wissenschaftlicher Unabhängigkeit wirkmächtiger zu gestalten.

Methoden

Es wurden zwei verschiedene methodische Ansätze verfolgt:

1) Über eine Abfrage der Web of Science Core Collection (WOS) wurde die Entwicklung von Forschungsfeldern insgesamt und in Österreich analysiert. Dafür wurde der Suchbegriff „biodiversity“ eingegeben. Für den Österreichbezug wurde die Zugehörigkeit auf österreichische Institutionen beschränkt (also im Suchfeld: biodiversity AND OG=(Austria)). Die Ergebnisse stammen vom 17.2.2025. Für einen Vergleich der Forschungsfelder wurden die „WOS categories“ verwendet und für die ersten 25 WOS Kategorien die Tabellen mit den Prozentangaben heruntergeladen. Da WOS bei der Kategorisierung Doppelnennungen akzeptiert, waren es jeweils in der Summe für die ersten 25 Kategorien mehr als 100 %.

2) Die Themen zur Erfassung und Gruppierung der Trends wurden nach eigener Einschätzung von den internationalen Diskursen zur Biodiversitätsforschung sowie zu Biodiversitätswissenschaft-Politik-Schnittstellen (v.a. IPBES und IPCC) abgeleitet.

Ergebnisse

Themen der Biodiversitätsforschung – in Österreich

Das Wort „biodiversity“ führte zu 285.836 Treffern in der Web of Science Core Collection (WOS). Davon sind an 5.238 Publikationen Wissenschaftlerinnen und Wissenschaftler aus österreichischen Einrichtungen beteiligt. Ein Vergleich der ersten 25 WOS-Forschungsgebietskategorien im Hinblick auf Autor*innen aus Österreich zeigte nur wenige Unterschiede (Abb. 1). Die mit Abstand häufigsten Themenfelder sind Ökologie (*Ecology*), Umweltwissenschaften (*Environmental Sciences*) und Naturschutz (*Biodiversity Conservation*). Ozeanographie (*Oceanography*) und Bodenforschung (*Soil Science*) hatten eine vergleichsweise geringere Häufigkeit, dafür waren Mykologie (*Mycology*) und Paläontologie (*Paleontology*) in Österreich präsenter, lagen jedoch auch nur im einstelligen Prozentbereich.

¹ <https://www.biodiversityaustria.at/>

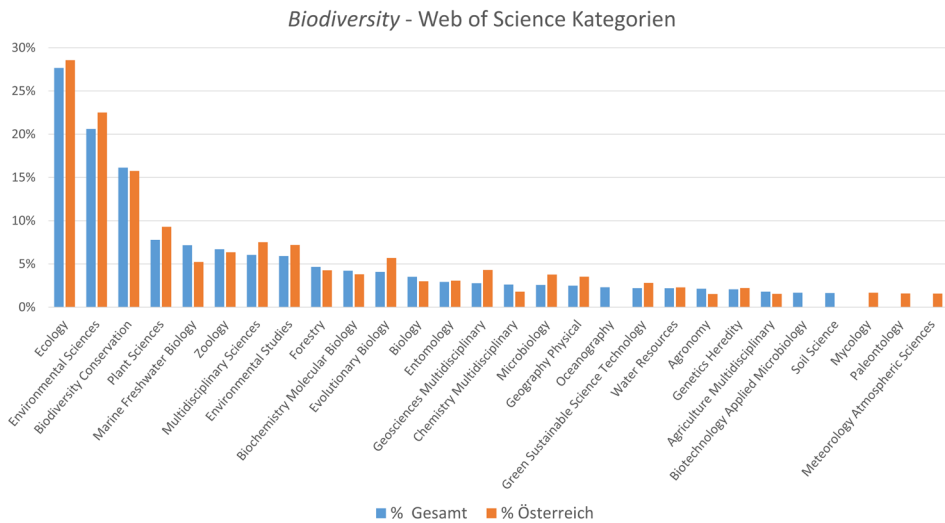


Abb. 1: Ein Vergleich der WOS Kategorien für sämtliche „biodiversity“-Publikationen (blau, $N = 285.836$) sowie die unter Beteiligung österreichischer Einrichtungen (rot, $n = 5.238$) | **Fig. 1:** A comparison of the WOS categories for all „biodiversity“ publications (blue, $N = 285,836$) and those involving Austrian institutions (red, $n = 5,238$).

Die digitale Zugänglichkeit von Daten und Informationen steigt

Ein wesentlicher Trend ist, dass die digitale Zugänglichkeit von Biodiversitätsdaten enorm steigt. So sind beispielsweise über das online Portal von GBIF (*the Global Biodiversity Information Facility*)² über drei Milliarden Datenbankeinträge erfasst, mit zunehmender Bemühung, die Datenqualität für Nutzer besser einschätzbar zu gestalten (Waller et al. 2021).

Auch die naturkundlichen Sammlungen werden weiter erschlossen und zunehmend digital zugänglich gemacht, sei es über Forschungsinfrastrukturen, in Österreich beispielsweise OSCA (*Open Scientific Collections Austria*; Korth et al. 2025), welche digitale Kataloge und Digitalisate zugänglich machen soll, oder die nationale Initiative ABOL (*Austrian Barcode of Life*). Letztere erstellt DNA-Barcoding-Daten die, wie viele andere internationale Projekte, zur globalen Initiative BOLD (*The Barcode of Life Data System*; Ratnasinga & Hebert 2007), beitragen und ein Referenzsystem verifizierter taxonomischer Information (wissenschaftliche Sammlungen) und genetischen Daten darstellt. Für den Zugang zu weiteren Informationen und v.a. Literatur spielt ZoBoDat eine herausragende Rolle (Malicky et al. 2022).

2 <https://www.gbif.org/>

Die Biodiversitätsforschung integriert neue Hochdurchsatz-Methoden

Die Biodiversitätsforschung und mit ihr eng assoziierte Forschungsfelder wie Evolutionsbiologie, Ökologie oder Naturschutzforschung profitieren von neuen Entwicklungen insbesondere im Bereich der Genetik (Davis & Knapp 2024; Hogg 2024; Kapun et al. 2025), aber auch den neuen Möglichkeiten der Visualisierung sowie der Bioinformatik (Wühl et al. 2021). Diese neuen Hochdurchsatz-Methoden revolutionieren die Einsichten in mikroevolutive Prozesse ebenso wie in funktionelle Zusammenhänge.

Die Biodiversitätsforschung arbeitet hochintegrativ

Die steigende digitale Verfügbarkeit von Informationen verbunden mit der intensiven Entwicklung von Standards ermöglicht die Verknüpfung von Biodiversitätsinformationen über sehr unterschiedliche Disziplinen hinweg (Otsu & Maso 2024). Damit wird die Biodiversitätsforschung, die intrinsisch interdisziplinär aufgestellt ist und die unterschiedlichsten Einrichtungen verbindet (Geschke & Vohland 2018), noch wirksamer. Aber auch schon die Taxonomie als Grundlagenwissenschaft der Biodiversitätsforschung arbeitet integrativ und berücksichtigt weiterhin sowohl verschiedene methodische Ansätze als auch interdisziplinäre Forschung (Padial et al. 2010; Zamani et al. 2022).

Das Bewusstsein für Ungerechtigkeiten steigt

Ein weiterer zu beobachtender Trend ist, dass die gerade sehr dominante Forschung zum kolonialen Erbe zu einem erhöhten Geschichtsbewusstsein und Bewusstsein zu den Erwerbskontexten nicht nur kulturwissenschaftlicher, sondern auch naturhistorischer Sammlungen (Schölnberger 2021; Raja et al. 2022), botanischer Gärten (Neves 2024) und epistemischer Ansätze (Zwart et al. 2024) führt. Die Diskussionen gehen also über die kolonialen Aspekte hinaus und befassen sich grundsätzlicher mit westlichen epistemischen Hegemonien sowie Geschlechtergerechtigkeit (Bossert et al. 2024).

Biodiversität wird zunehmend als Wirtschaftsfaktor wahrgenommen

Das internationale Wirtschafts-Politik Netzwerk *Digital Life Design* (DLD) hat erstmalig im Jahr 2024 ein *DLD Nature* veranstaltet, u.a. mit Ursula von der Leyen, welche die Strategie zum New Green Deal ausgeführt hat (Von der Leyen 2024), oder Johann Rockström, der eindringlich vor den wirtschaftlichen Folgen des Verlustes von Ökosystemen gewarnt hat³.

Die parallel wachsende Forschung zur Finanzierung von Biodiversität folgt verschiedenen theoretischen Rahmen, von der Finanzierung der sogenannten Ökosystemdienstleistungen wie Produkten oder Prozessen bis hin zur Vermeidung von Schäden durch den Verlust von Biodiversität; dabei werden Instrumente wie beispielsweise Ökokompensierung oder Ökotourismus analysiert (z. B. Chopra et al. 2024). Allerdings stellte das letztgenannte Autorenteam in ihrer Literaturanalyse auch fest, dass trotz des erhöhten Bewusstseins der wirtschaftlichen Abhängigkeit von natürlichen Ressourcen die Finanzierung von biodiversitätsrelevanten Investitionen sogar zurückging.

3 <https://www.youtube.com/watch?v=5d-UqYrCcgo>

Biodiversitätsforschung ist und bleibt auch politisch

Biodiversität war von Anfang an auch ein politischer Begriff, da er im Rahmen der Entstehung der drei großen Umweltkonventionen in Rio de Janeiro im Jahr 1992 mit dem Abkommen zur Biologischen Vielfalt (CBD – *Convention of Biological Diversity*) die öffentliche Bühne betreten hat. Der globale Biodiversitätsrat IPBES (*Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services*) wurde explizit dafür angelegt, im Auftrag der Regierungen die Ergebnisse der Biodiversitätsforschung zu verschiedenen Fragestellungen zu synthetisieren – und vor allem zu legitimieren (Vohland & Nadim 2015). Es gab schon immer Interessenskonflikte zwischen verschiedenen Anspruchsgruppen, der aktuellste und in Österreich sehr lautstark ausgetragene Disput ist sicherlich jener um die EU-Verordnung zur Wiederherstellung der Natur (*Nature Restoration Law*; z.B. APA 2024).

Diskussion

Datengrundlage

Die WOS-Kategorien wurden verwendet, um eine „unabhängige“ Datengrundlage zu haben, wohl wissend, dass über Zuordnungen und Terminologien im Detail gestritten werden kann. Zudem erfasst WOS für die Fragestellung nach aktuellen Trends nur einen Teil der Publikationen und insbesondere die im Bereich der Biodiversitätsforschung relevante „graue“ Literatur wird nicht ausreichend berücksichtigt. Daher wurde auch über Google Scholar, ZooBoDat, ZENODO etc. nach entsprechenden Publikationen gesucht. Die Auswahl der Trends ist entsprechend subjektiv und basiert auf eigenen Einschätzungen.

Der Trend hin zu stärker integrativer Forschung in der Biodiversitätsforschung ist nicht ganz neu; Stork & Astrin (2014) haben in einer bibliographischen Studie herausgearbeitet, dass die Verbindung zur Klimaforschung über die Jahre intensiver wurde und soziale Aspekte zugenommen haben. Dennoch ist zu konstatieren, dass Sozial- und Wirtschaftswissenschaften bei Umweltfragen immer noch eine unzureichende Rolle spielen (Tan et al. 2023). Ebenso gibt es in der Biodiversitätsforschung ein starkes Ungleichgewicht im Hinblick auf geographische Repräsentation zugunsten der westlichen Staaten (Tydecks et al. 2018), was natürlich auch die Verfügbarkeit von Literatur für Trendanalysen beeinflusst.

Was folgt aus den Trends?

Es konnte gezeigt werden, dass Biodiversitätsforschung sehr innovativ und integrativ ist und mit modernen Methoden arbeitet. Sie wird in gesellschaftlich relevanten Bereichen wie Politik und Wirtschaft zunehmend wahrgenommen, ohne dass jedoch die politischen Ziele der CBD oder weiter heruntergebrochener europäischer oder nationaler Biodiversitätsstrategien erreicht wurden. Im Gegenteil, der Verlust von Lebensraum, – durch z. B. Zersiedelung oder Flächeninanspruchnahme für Infrastrukturen oder Rohstoffabbau – und

damit der Verlust an Arten schreitet schneller voran als je zuvor. Die Frage ist also, wie können wir Biodiversitätsforschung gestalten, so dass sie

- *exzellent und unabhängig bleibt*
- *und zugleich wirksamer hinsichtlich eines gelingenden Natur-Mensch-Kultur Verhältnisses wird?*

Eine Strategie ist, Partnerschaften mit Akteursgruppen aus dem wirtschaftlichen Bereich, die einen wesentlichen Einfluss auf die Biodiversität haben, allen voran die Land- und Forstwirtschaft, zu schaffen und zu erweitern (Takacs & O'Brien 2023). Wichtig ist zudem die Einbindung von Sozialwissenschaften und natürlich grundsätzlich der Zivilgesellschaft und ihrer politischen Repräsentation.

Landnutzer als Partner gewinnen: Partnerschaften mit Land- und Forstwirtschaft

Es gibt überschneidende Interessen zwischen Land- und Forstwirtschaft und Naturschutz wie beispielsweise die Erhaltung von gesunden Böden, sauberem Wasser und resilienten Agrarökosystemen. Und es gibt konfligierende Interessen wie die Anzahl an Beikräutern („Unkräutern“), Strukturelementen oder Diversität angebaute Kulturen. Einige Interessenskonflikte sind weniger naturwissenschaftlich als durch die ökonomischen Rahmenbedingungen oder das Gefühl von Freiheitsbeschränkungen durch Verbote bedingt.

Es gibt in Österreich bereits Austauschforen wie die Biodiversitätskommission, die durch das Bundesministerium für Land- und Forstwirtschaft, Klima- und Umweltschutz, Regionen und Wasserwirtschaft (BMLUK) einberufen wird, sowie das durchaus effektive Agrarumweltprogramm ÖPUL (Wöckinger 2023). Ein wichtiger Mechanismus dabei ist die Aneignung von gemeinsamen Zielen durch die Beteiligten, welches in dem Zitat eines Landwirtes: „Durch das Monitoring werden die Naturschutzziele auch zum eigenen Anliegen⁴“ wunderbar zum Ausdruck gebracht wird. Grundsätzlich würde auch die Forstwirtschaft von einer höheren Anzahl an Arten im Wald profitieren (Weiskopf et al. 2024). Um jedoch wirklich vertrauensvoller zusammenzuarbeiten, braucht es eine gemeinsame Identifikation des Problems und entsprechende inter- und transdisziplinäre Forschungsprojekte, beispielsweise zur Frage, wie die Resilienz oder die Bodenfruchtbarkeit unter nicht nur Biodiversitätsaspekten, sondern auch unter ökonomischen Aspekten zu berücksichtigen wäre. Zudem ist es nötig, auch sozialwissenschaftliche Expertise einzubinden, die beispielsweise Hinweise auf die persönlichen und strukturellen Handlungskapazitäten der beteiligten Landwirt*innen oder Forstleute gibt (Mehring et al. 2023). Auch der Österreichische Biodiversitätsrat sieht sich als Schnittstelle zwischen Wissenschaft und Praxis und setzt sich dafür ein, den Wert der Biodiversität und ihren gesellschaftlichen Nutzen sichtbar zu machen und bei der Lösung von Interessenkonflikten zu unterstützen.

4 <https://www.naturschutzmonitoring.at/de/biodiversitaet/>

Partnerschaften mit Industrie- und Wirtschaft

Grundsätzlich gibt es auch mit Industrie- und Wirtschaftsunternehmen gemeinsame Interessen, seien es die Sicherung natürlicher Ressourcen, die Steigerung der Innovationskraft Europas durch Entwicklungen in der Bioökonomie (Mirzabaev et al. 2015) oder im Feld der BioInnovation (Gebeshuber 2022; Nieuwenhoven et al. 2024; Saint-Sardos et al. 2024).

Neue Instrumente der Finanzwirtschaft wie die Green Bonds hören sich erstmal vielversprechend an. Ein Beispiel ist das Energieunternehmen Verbund, welches mit Green Bonds wirbt, die Ausgleichsleistungen im Rahmen zweier EU LIFE Projekte bei der Errichtung von Wasserkraftwerken mitfinanzieren (Verbund 2024). Allerdings ist die Wirksamkeit all dieser Finanzströme begrenzt, auch angesichts der hohen Summen, die immer noch klar umweltschädliche Vorhaben finanziell unterstützen (Grabbe & Moffat 2024).

Ein Zitat einer aktuellen Masterarbeit resümiert, „nur wenn Biodiversitätsbelange in die Prozesse, Entscheidungsfindungen und Strategien integriert werden, können negative Auswirkungen von Unternehmensaktivitäten auf die biologische Vielfalt minimiert und bestenfalls gleichzeitig positive Beiträge zu ihrer Erhaltung geleistet werden. Da derzeit entsprechende Vorstöße aus dem Unternehmenssektor heraus kaum zu beobachten sind, ist es die Aufgabe politischer Entscheidungsträger, das Mainstreaming zu forcieren“ (Lunkenheimer 2024, S. 65). Dieses Zitat macht sehr deutlich, dass die aktuellen finanziellen Anreize für die Unternehmen zugunsten eines nachhaltigen und umweltbewussten Wirtschaftens nachgebessert werden müssen.

Die gesellschafts-politische Dimension

Das Ungleichgewicht zwischen biodiversitätsschädigenden und biodiversitätsfördernden Investitionen und Subventionen hat viele Gründe; dazu gehören insbesondere wirtschaftliche Rahmenbedingungen, die den Verbrauch von Natur zu Gunsten von Teilen der globalen Bevölkerung und zu Lasten der Allgemeinheit stattfinden lassen. Zudem beobachten wir auch in Österreich eine Polarisierung der Gesellschaft, die durch populistische Parteien instrumentalisiert wird, aber ihren tieferen Grund auch in einer Entkopplung zwischen der Lebenswirklichkeit vieler Menschen von Wissenschaft und Politik sowie Natur hat (Rekker 2021; Janss et al. 2023). Zudem sind Menschen durch die multiplen Krisen sowie durch eine als schwieriger wahrgenommene persönliche Lebensplanung verunsichert. Wichtig ist es entsprechend, auch in der Biodiversitätsforschung viel stärker auf soziale Aspekte einzugehen, die auch Aspekte der Umweltgerechtigkeit und Geschlechtergerechtigkeit beinhalten (Thaler & Karner 2024). Möglicherweise können auch die Kirchen stärker als gesellschaftlicher Partner gewonnen werden. Beispielsweise hat Papst Franziskus (2016) mit der Enzyklika „Laudato Si“ den Zusammenhang von Sozial- und Umweltproblemen dargestellt.

Biodiversitätsforschung braucht historisches Bewusstsein, um zu einer global gerechten Welt beizutragen

Vielleicht war es ein strategischer Fehler, die Biodiversität als Teil des Regelwerkes der CBD dem Eigentum einzelner Staaten zuzuschreiben. Die rechtlichen Konsequenzen des Abkommens sind nicht immer praktisch durchführbar, wie zuletzt die Diskussionen um

DSI (Digitale Sequenz-Information) gezeigt haben – Mikroben und ihr Genpool sind beispielsweise ubiquitär. Aber auch für größere Organismen spielen Landesgrenzen keine Rolle, seien es Zugvögel oder migrierende Savannenbewohner.

In vielen Ländern des globalen Südens gibt es sehr viele Arten, die auch als Medizinal- oder andere potentielle Nutzpflanzen eine wichtige Versicherungsfunktion aufweisen. Hier wie dort verringert sich die Anzahl der Arten aufgrund von Landnutzungskonflikten zwischen Ökosystemen und anderen Nutzungen wie Städten, Infrastrukturen oder Land- und Forstwirtschaft, Übernutzung, Schadstoffen und zunehmend auch den Folgen des Klimawandels.

Globale Kooperationen können dazu führen, voneinander zu lernen und die verschiedenen Zugänge zum Mensch-Natur Verhältnis zu verstehen (White et al. 2023). Der naturwissenschaftlich geprägte westliche Zugang zu Natur, zu Organismen, arbeitet stark über eindeutige Namensbenennungen, taxonomische Standards oder Datenbanken. Im Gegensatz dazu verweist ein weniger abstrakter Zugang zu Natur stärker auf das relationale Mensch-Natur Verhältnis (Henrich 2022). Das kann sich in einem anderen Umgang mit dem Tod ausdrücken und findet sich beispielsweise in den auf Harmonie angelegten Konzepten wie „Mutter Natur“ in Lateinamerika oder „Satoyama Satoji“ (Harmonie und Dankbarkeit gegenüber der Natur) in Japan aus, welches das Leitthema der CBD Vertragsstaatenkonferenz (*Conference of the Parties* (COP)) 10 in Nagoya, Japan, war. „Mutter Natur“ und „Harmonie“ sind deutlich andere Naturkonzepte als die „Ökosystemaren Dienstleistungen“ des Globalen Westens, ein Thema, was auch die Arbeit in IPBES prägt (Borie & Hulme 2015).

Kooperationen zwischen wissenschaftlichen Einrichtungen unterschiedlicher Länder können durch gemeinsame Projekte, den Austausch von Forschenden, das gemeinsame Bearbeiten von Dokumenten im Rahmen von IPBES etc. umgesetzt werden. Die aktuelle Aufmerksamkeit zu hegemonialen Fragen kann also auch als Chance gesehen werden, über den Dialog mit den Herkunftsgesellschaften von beispielsweise Sammlungsobjekten mehr über die verschiedenen Mensch-Natur Verhältnisse zu lernen und ein gemeinsames Verständnis zu den unterschiedlichen Zugängen zu entwickeln, um letztlich den globalen politischen Diskurs zu Biodiversitätsfragen zu bereichern und effektiv zu gestalten.

Biodiversitätsforschung muss in der Gesellschaft verankert sein

Ein wichtiger Ansatz zur Verankerung von Wissenschaft und Forschung in der Gesellschaft ist Citizen Science, die Beteiligung von Menschen verschiedenster Herkunft und Sozialisation in wissenschaftlichen Projekten und Biodiversitätsmonitorings (Kaufmann & Lindner 2021; Vohland et al. 2021). In Österreich ist speziell das Programm „Sparkling Science“ herauszuheben, welches Schulkinder in die Forschung einbindet, damit sehr integrativ ist und eine langfristige positive Wirkung erzielt (Ringel et al. 2014; Tiefenthaler 2018).

Zunehmend wird auch deutlich, dass fachliche Informationen wichtig sind, aber die emotionale Komponente, oder anders ausgedrückt, die persönliche Beziehungsebene zur Natur, sehr viel mehr Berücksichtigung als bisher in der Kommunikation von Biodiversität und Biodiversitätsforschung in der Wissenschaftsvermittlung und öffentlichen Kommunikation erhalten muss; ebenso wichtig ist die Formulierung von positiven Zielen (de Lange et al. 2022).

Schlussfolgerungen

Es gibt sehr viele Daten und sehr viel Wissen zur Biodiversität und den Gründen für den Verlust von genetischer Vielfalt, Arten und Lebensräumen. Das Wort „Biodiversitätskrise“ ist aber sehr abstrakt und motiviert Menschen nicht zum Handeln. Es wäre zielführender, die direkt menschenbezogenen Probleme wie beispielsweise den Verlust an fruchtbarem Boden, den Rückgang von Bestäubern, die Abnahme von Resilienz, den Verlust von Ästhetik und freiem Naturerleben oder eben auch gesundheitliche Schäden, wirtschaftliche Folgen von Überflutungen oder soziale Auswirkungen von Umweltmigration konkreter und auch gemeinsam mit den Betroffenen zu formulieren. Genauso wichtig ist es, im Rahmen von Kooperationen zwischen Biodiversitätsforschenden und anderen Akteuren gemeinsam Zielvorstellungen und Visionen zu formulieren, die an die reale Lebenswelt aller Beteiligten anschließen, seien es Wertesysteme oder ökonomische Interessen.

Für all diese Kooperationen sind Prozesse wichtig. Der Prozessgestaltung muss viel mehr Aufmerksamkeit als bisher gewidmet werden. Ansätze partizipativer Prozesse gibt es ja bereits. Beispielhaft zu nennen wären die Methoden transdisziplinärer Forschung, Citizen Science, Co-Design oder Reallabore. Hier ist die Biodiversitätsforschung gefragt, noch integrativer zu werden, und die Akteure wie wissenschaftliche Institutionen, wirtschaftliche Unternehmen oder auch Fördereinrichtungen sind aufgefordert, solche nachhaltigen Prozessgestaltungen offensiv zu unterstützen.

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Biodiversity Days 2025: Where Science Meets Society

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The biodiversity crisis poses severe threats to livelihoods, societal stability, and environmental sustainability, with scientific skepticism often hindering urgently needed conservation measures. Participatory science communication and accessible dissemination of research can bridge the gap between science and society, fostering engagement, trust, and informed decision-making. Educational formats – such as programs, events, guided tours, and workshops – make science tangible and relevant for diverse audiences, as demonstrated during *Biodiversity Days 2025*, where a session organized by the Faculty of Life Sciences at the University of Vienna attracted 25 contributions, highlighting the strong demand for dialogue. Three initiatives at the University of Vienna exemplify effective approaches: the *Experience Science Network*, which connects outreach activities across disciplines and brings research into public spaces; the *Teaching and Learning Lab „Future Lab Life Skills: Nutrition & Sustainability“*, which links university and school education to raise awareness of the interconnections between nutrition, climate change, and biodiversity; and the *Konrad Lorenz Research Center*, which provides hands-on experiences in behavioral biology focusing on wild animals in their natural habitats, and fosters public participation through citizen science with positive impacts on regional development. Together, these initiatives demonstrate that targeted communication and participatory formats can strengthen the science–society connection, increasing acceptance of biodiversity conservation and supporting sustainable development.

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Die Biodiversitätskrise bedroht Lebensgrundlagen, gesellschaftliche Stabilität und ökologische Nachhaltigkeit und wird durch wissenschaftsskeptische Haltungen, die dringend notwendige Schutzmaßnahmen behindern, zusätzlich verschärft. Partizipative Wissenschaftskommunikation und der barrierefreie Zugang zu Forschungsergebnissen können die Kluft zwischen Wissenschaft und Gesellschaft überbrücken, Engagement und Vertrauen fördern sowie fundierte Entscheidungsfindung unterstützen. Bildungsformate wie Programme, Veranstaltungen, Führungen und Workshops machen Wissenschaft für unterschiedliche Zielgruppen greifbar und relevant. Dies zeigte sich während der *Biodiversitätstage 2025*, bei denen eine von der Fakultät für Lebenswissenschaften der Universität Wien organisierte Sitzung mit 25 Beiträgen das große Bedürfnis nach Dialog deutlich machte. Drei Initiativen der Universität Wien verdeutlichen wirksame Ansätze: das *Netzwerk Experience Science*, das Outreach-Aktivitäten über Disziplinen hinweg vernetzt und Forschung in den öffentlichen Raum bringt; das *Teaching and Learning Lab „Future Lab Life Skills: Ernährung & Nachhaltigkeit“*, das Universitäts- und Schulbildung verbindet, um das Bewusstsein für die Zusammenhänge zwischen Ernährung, Klimawandel und Biodiversität zu stärken; sowie die *Konrad Lorenz Forschungsstelle*, die altersgerechte, praxisorientierte Erlebnisse in der Verhaltensbiologie mit Fokus auf Wildtiere in ihrem natürlichen Lebensraum bietet und durch Citizen-Science-Projekte das öffentliche Interesse fördert und Impulse für die regionale Entwicklung gibt. Gemeinsam zeigen diese Initiativen, dass zielgerichtete Kommunikation und partizipative Formate die Verbindung zwischen Wissenschaft und Gesellschaft stärken, die Akzeptanz des Biodiversitätsschutzes erhöhen und nachhaltige Entwicklung unterstützen können.

Keywords: sustainability, education, subject didactic, science, society, science communication, third mission, biodiversity.

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Introduction

The biodiversity crisis threatens essential ecosystem services, leading to health and economic repercussions (Abbasi et al. 2023). It has profound implications for livelihoods, societal challenges, and potential conflicts, emphasizing the need for effective science communication. As biodiversity declines at an alarming rate due to habitat destruction, pollution, overexploitation, climate change, and invasive species, the consequences ripple across all aspects of life (Pörtner et al. 2023). Economic instability, displacement, and increased vulnerability to natural disasters are only a few examples (Pörtner et al. 2023).

Addressing the biodiversity crisis requires coordinated and informed action on multiple levels – from policymakers, decision makers in education and scientists to local communities and individuals (Pörtner et al. 2023). Engaging the public through educational programs, workshops, and guided tours can enhance understanding and acceptance of scientific facts (Geschke et al. 2023). However, scientific skepticism, misinformation, and a general disconnect between science and the public hinder progress. Despite the abundance of data and warnings from experts, many people still struggle to grasp the urgency of biodiversity loss to their own lives (Bradshaw et al. 2021). Scientific findings often remain locked within academic publications or communicated in ways that are inaccessible to non-specialists. As a result, the gap between scientific knowledge and societal action gets broader. Thus, fostering a culture of understanding and collaboration between science and community is vital. It is also an essential task of educational systems to encourage engagement with core challenges and should be part of curricula over all types of schools (Rudolph 2023).

Participatory science communication can play a crucial role in bridging the gap between the limits and opportunities of scientific knowledge and the need for emotional engagement and understanding at both individual and community levels, fostering awareness and motivating action against biodiversity loss (Lees et al. 2021). Moreover, participatory approaches invite collaboration, dialogue, and shared ownership of current levels of awareness and knowledge. When people are actively involved in scientific inquiry – through citizen science projects, co-designed research, and/or local conservation initiatives – they are more likely to understand and trust the robustness of the results. This trust, in turn, fosters a sense of responsibility and empowerment, encouraging them to act on the knowledge they have gained. Such an understanding of science should be cultivated from an early age through appropriately designed school education (Campbell & Howitt 2024).

Tab. 1: Overview of the different initiatives, target groups and formats, including the number of people reached. – **Tab. 1:** Überblick über die verschiedenen Initiativen, Zielgruppen und Formate, einschließlich der erreichten Personenzahlen

Initiative – Organisation	Target Groups	Formats	People reached (directly and indirectly)
Experience Science Network*	Children School Classes Groups Interested Participants Students	Events Courses, Workshops, Online presence, publications	> 20.000 per year
FuLaLiS	Students Teachers Children School Classes	Events Courses, Workshops, Online presence, publications Subject-Didactic Research Teaching	> 1.000 per year
KLF Grünau	Children School Classes Groups Interested Participants Students	Events Courses, Workshops, Online presence, publications	> 9.000 per year

* included in this context: AECC Biologie, Monkey Mountain Affenberg,
Botanical Garden, Haidlhof Research Station, Zoologische Sammlung

Another key element of effective science communication is low-threshold dissemination – the practice of making scientific information accessible to a broad audience, regardless of prior knowledge, education level, or social background. This involves highlighting relevant aspects, using clear, jargon-free language, employing visual storytelling, incorporating culturally relevant examples, and offering multiple formats to reach different learning styles and communities. It also means meeting people where they are – both literally and figuratively: in schools, libraries, museums, community centers, public parks, and online spaces as well as in places where research “happens” and “lives” such as teaching and learning laboratories (*Lehr-Lern-Labore*). The goal is to remove barriers to engagement and make science feel inclusive, relevant, and meaningful to everyday life (Wilkinson & Webber 2024).

When participatory methods and accessible communication are combined, they can transform passive awareness into active engagement (McKinnon & Voos 2014). People who feel heard, respected, and informed are more likely to support biodiversity-friendly policies, make environmentally conscious choices, and advocate for systemic change. Various formats have proven effective in bringing science to life and inspiring action. Educational programs in schools and universities can nurture curiosity and environmental literacy from a young age. Public events such as science festivals, exhibitions, and open labs create opportunities for informal learning and personal interaction with researchers. Guided nature tours and citizen science workshops allow participants to observe biodiversity firsthand, collect data, and contribute to real-world projects (Bonney et al. 2016). These experiences not only convey

scientific facts but also foster emotional connections to the natural world – connections that are crucial for motivating long-term behavioral change.

The session “Begegnungen von Wissenschaft und Gesellschaft: Orte, Programme, Mehrwert, Perspektiven” at the “Tage der Biodiversität 25” held in Vienna (Austria) in February 2025 brought together actors involved in science communication to discuss the advantages and challenges associated with this approach. The call for abstracts was highly successful in terms of registrations: 25 contributions reflected the strong interest in, and need for, exchange in the field of science communication. We present here the outcomes of the presentations, focusing on the following three contributions from the session:

1. The *Experience Science Network* at the Faculty of Life Sciences
2. The Teaching and Learning Lab *Future Lab Life Skills: Nutrition & Sustainability*
3. The hands-on experiences in behavioral biology at the Konrad Lorenz Research Center

We base the present contribution on the current discourse of science communication and sustainability, share our experiences and report lessons learned for future research. An overview of the different initiatives, target groups and formats, including the number of people reached is presented in Tab. 1.

Public engagement at the Faculty of Life Sciences, University of Vienna

The Network “Experience Science” at the Faculty of Life Sciences, University of Vienna – Bringing Science to Life: The Role of Outreach and Networking in Fostering Scientific Literacy

In an increasingly scientific and technologically advanced society, fostering scientific literacy from an early age is essential. It empowers individuals to make informed decisions about their health, environment, and everyday lives, while also encouraging active political and civic engagement. Scientifically literate citizens are better equipped to understand the implications of global challenges – from climate change to pandemics – and to critically evaluate information in an era of misinformation (Howell & Brossard 2021). Science communication plays a pivotal role in supporting this vision. It not only enriches education and supports the development of informed citizens but also helps train highly qualified professionals and contributes to a nation’s overall innovation capacity and well-being.

At the Faculty of Life Sciences of the University of Vienna¹, Austria, research, teaching, and so-called “third mission” activities take place both at the main campus in Vienna and at several satellite locations (hereafter: *Außenstellen*) distributed across the country and

¹ <https://lifesciences.univie.ac.at/innovation-impact/experience-science/>

internationally, such as the La Gamba Tropical Field Station² in Costa Rica. These external sites are designed to serve as bridges between academia and the public, offering diverse and professionally curated formats for science communication. They span various disciplines, including behavioral biology, botany, zoology, biology and nutrition education, biodiversity, environmental protection, and sustainability.

Through tailored educational programs, public events, guided tours, exhibitions, and interactive workshops, these *Außenstellen* bring science out of the lab and into the lives of people from all walks of life. Their work is not only about presenting scientific facts but about engaging audiences emotionally and intellectually, creating memorable experiences that spark curiosity and inspire action.

In 2024, thanks to the initiative and collaboration of numerous individuals and with strong leadership from the Faculty of Life Sciences, a coordinated effort was launched to reflect on and analyze the current outreach activities, objectives, and target groups of these external units. This process of self-evaluation and strategic development resulted in the creation of a unified and forward-looking network known as *Experience Science*.

The *Experience Science Network* reflects a shared vision of interdisciplinary collaboration, mutual learning, and increased visibility of the Faculty's science communication initiatives. By pooling resources and expertise, the network aims to enhance the coherence, impact, and sustainability of outreach activities across all participating locations. It supports the development of participatory formats and the integration of cutting-edge research topics into public-facing events, ensuring that science is not only understood but also felt to be meaningful and relevant in today's world.

Key institutions within the network – such as the Konrad Lorenz Research Center³, the Botanical Garden⁴, the Haidlhof Research Station⁵, the Affenberg Research Station⁶, and the La Gamba Tropical Field Station – play a critical role in making science tangible and accessible. Whether it's studying endangered species, investigating animal cognition, or promoting the sustainable use of biodiversity, these efforts highlight the relevance of research to both local and global issues. Science communication here is not a one-way transmission of knowledge, but a dialogue – an invitation to explore the natural world and understand the science that shapes our future.

The work of the *Außenstellen* is further strengthened through collaborations with units like the Austrian Educational Competence Center Biology⁷ and the Working Group Subject Didactics in Home Economics and Nutrition⁸ which is located at the Department of Nutritional Sciences and the Center for Teacher Education. These departments contribute pedagogical and subject didactic expertise and creative formats in teaching and learning that

2 <https://www.lagamba.at/en/>

3 <https://klf.univie.ac.at/de/>

4 <https://botanischergarten.univie.ac.at/en/>

5 <https://haidlhof.org/>

6 <https://affenberg.univie.ac.at/>

7 <https://aeccbio.univie.ac.at/>

8 <https://nutrition.univie.ac.at/forschung/fachdidaktik-haushaltsoekonomie-und-ernaehrung-asso-z-prof-dr-paed-habil-claudia-maria-angele/>

highlight key issues in sustainability, nutrition education, and environmental awareness. Their collaboration enriches the broader outreach landscape and deepens the pedagogical and the subject didactic impact of the network's activities.

The formation of the *Experience Science Network* highlights the importance of strategic networking and synergy development within academic science communication. In a field where visibility, relevance, and public trust are all crucial, effective collaboration multiplies impact. Through shared infrastructure, coordinated programming, and a unified identity, the network enhances each location's reach while maintaining the unique character and disciplinary focus of each site. Furthermore, it opens up new possibilities for joint funding, evaluation, and long-term planning, positioning the Faculty as a leader in innovative science communication within Austria and beyond.

Importantly, the initiative also aligns with broader European and global trends that emphasize open science, citizen engagement, and responsible research and innovation (RRI). Science communication is no longer viewed as an optional extension of research, but as an integral part of the scientific process – one that ensures relevance, accountability, and public involvement. The *Experience Science Network* stands as a model of how universities can rise to this challenge by embedding engagement into their institutional tasks.

As demands for societal dialogue, scientific accountability, and ecological literacy grow, the Faculty of Life Sciences' commitment to outreach exemplifies the potential of science communication to transform not only minds but communities. The *Experience Science Network* provides an infrastructure and ethos for this transformation. By connecting research, education, and society through engaging, locally rooted, and globally relevant programs, it demonstrates how science can be both rigorous and resonant – something to be experienced, shared, and lived.

Nutritional sciences and sustainability, nutrition education, teacher education: The Teaching and Learning Lab “Future Lab Life Skills – Nutrition and Sustainability”

Against this background, the teaching and learning laboratory *Future Lab Life Skills (FuLaLiS) – Nutrition and Sustainability* is currently being established at the Department of Nutritional Sciences (Faculty of Life Sciences) and the Center for Teacher Education at the University of Vienna. This future-oriented lab focuses on the didactic development of topics related to the complex interrelationships between nutrition and sustainability. The didactic concept developed by Angele (2023) is innovative in the context of nutrition education and secondary school teacher professionalisation internationally. Construction of the lab was completed in autumn 2025. Development and implementation of the first seminar project for student teachers in summer term 2026 – including workshops for school classes – will be scientifically monitored as part of a PhD project (Enghart 2025).

FuLaLiS offers an innovative link between research, teaching, and third-mission activities in the Subject Didactics of Home Economics and Nutrition. It is designed as a multi-purpose space: a venue for subject-specific teacher training, an extracurricular learning centre for pupils, a platform for science communication, and a place for professional development for nutrition educators and for subject-didactic research. Teaching and learning labs bring

together actors from multiple groups – students, pupils, teachers, educators, researchers, and experts from diverse sectors. Research-based, subject-related, and interdisciplinary learning are central for all participants. For teacher education, the lab provides explicit opportunities to link theory and practice by allowing prospective teachers to design, test, and refine their teaching strategies based on scientific criteria.

The thematic focus includes nutrition, consumption, and sustainability – key issues for both global society, individual health and sustainable lifestyle. In addition to nutritional sciences, the lab draws on transdisciplinary frameworks such as Planetary Health and the One Health approach, highlighting that human health, diets, and food security ultimately depend on the health of the planet (Gruetzmacher et al. 2015; Willett et al. 2019). Education plays a crucial role in both approaches, as lack of knowledge about these interconnections is considered a major factor in exceeding planetary boundaries. It is a didactic question to clarify what competences people need in order to fulfill their responsibilities as global citizens and to act responsible in terms of sustainable nutrition and consumption. The associated challenges for the Subject Didactics of Home Economics and Nutrition lie above all in the research-led development and testing of innovative learning settings that focus on promoting informed judgement, and responsible action (Wagner-Kerschbaumer et al. 2023).

The lab's didactic principles follow the “knowing – valuing – acting” model, integrating science orientation, competence orientation, subject orientation, and action orientation (Angele et al. 2021).

FuLaLiS features three closely linked learning spaces:

- **Learning Room 1:** Seminar/discourse room with modern technology for analogue, digital, and hybrid learning.
- **Learning Room 2:** Demonstration and learning kitchen with fixed and mobile units.
- **Learning Room 3:** Laboratory for sensory experiments and other hands-on activities.

The integration of these spaces enables combined theoretical, sensory, and practical learning experiences. The lab will also support joint workshops across the *Experience Science Network* via digital connectivity, contributing directly to the sustainability goals of the University of Vienna through targeted knowledge transfer and science communication on topics such as sustainable diets, climate impacts, global health, and planetary health.

Behavioral Biology and Societal Literacy: The Konrad Lorenz Research Center: Bridging Science, Education, and Society through Behavioral Biology

The Konrad Lorenz Research Center (KLF), named after Nobel Laureate Konrad Lorenz, has, for over 50 years, stood as a bridge between the scientific study of animal behavior and the public's understanding of it. Established in 1973 and a core facility of the University of Vienna since 2012, the KLF has carved out a unique role in science and society: to study wild birds in their natural environment using evolutionary, phylogenetic, mechanistic, and developmental perspectives – while sharing that knowledge directly with the people whose lives and landscapes these birds inhabit.

At its heart, the KLF operates on a simple but profound conviction: science should not be confined to lecture halls and journals – it should be lived, experienced, and shared. Through a combination of cutting-edge research, hands-on outreach, and participatory approaches, the center shows how behavioral biology can become part of people's lives, sparking curiosity, understanding, and care for the natural world.

Citizen science is one of KLF's hallmarks. Whether through large-scale events like the *Long Night of Research* or intimate settings such as *KinderUniAlmtal*⁹, people of all ages are invited to observe, ask questions, and even collect data. Open-access publications such as *Frontiers for Young Minds*¹⁰ distil complex research into age-appropriate formats, ensuring that even the youngest readers can engage with science (Puehringer-Sturmayer et al. 2021; Frigerio et al. 2023, 2024). These are not only educational encounters – they are emotional ones, fostering a sense of wonder and responsibility that often lasts a lifetime.

Each year, KLF reaches around 10,000 people, many through collaborations with local schools. These partnerships give students and teachers authentic, first-hand experience with research while enriching the centre's own datasets. Such collaborations also strengthen the University of Vienna's presence in rural regions, contributing to regional development while building a scientifically informed public.

A major step forward in this mission is the creation of the *Open Science Center*¹¹ in the *Cumberland Wildpark*¹², supported by the State of Upper Austria. This physical space invites visitors to meet researchers, witness science in action, and understand how knowledge is built – deepening the dialogue between science and society.

The evidence from KLF's projects is clear:

1. **Data quality** – With proper training, volunteers of all ages produce reliable, publishable data.
2. **Educational impact** – Participating in research strengthens conceptual understanding, critical thinking, teamwork, and communication skills (Hirschenhauser et al. 2019, 2022).

These findings reinforce what the literature already shows (Agre & Leshner 2010; Richter et al. 2019): public engagement is not an optional extra but a core part of science, especially in areas – like climate change and biodiversity loss – where societal action is essential. Behavioral biology is particularly powerful here because animal behavior is immediately observable, relatable, and rich with stories.

Challenges remain – public mistrust in science, polarised media, and competing narratives – but the KLF's example shows that scientific rigour and public accessibility are not mutually

9 <https://www.kinderuni-ooe.at/kinderuni-ooe/almtal/>

10 <https://www.kinderuni-ooe.at/kinderuni-ooe/almtal/>

11 <https://klf-opensciencecenter.univie.ac.at/>

12 <https://wildpark.at/>

exclusive. They are mutually reinforcing. The center's programs have inspired national prize-winning student projects and long-term conservation support.

The forthcoming *Open Science Center* will take this work further, offering real-time data, workshops, and participatory research opportunities. This integration of open data, technology, and education will help ensure that conservation becomes a shared societal responsibility (Levis et al. 2024; see also the UNESCO Recommendation on Open Science, 2021). In the end, the story of citizen science and bird behavior is the story of how science, when opened to the public, can transform not only what we know – but how we care (Ballard et al. 2024).

Discussion

In science – as in nature – connections matter. The exploration of synergies and networking in academia, particularly in outreach and science communication, reveals that relationships are not peripheral to the work of science; they are central to it. More than just a professional strategy, networking has become a cornerstone of how knowledge is created, shared, and applied within both academic and public domains. It facilitates meaningful collaborations and amplifies the outreach and impact of scientific communication efforts, making science more visible, accessible, and responsive to societal needs.

Academic networking serves multiple functions. At its core, it fosters relationships that can lead to collaborative research, joint publications, new project development, and even career advancement. According to Borger (2024), individuals who engage in sustained networking efforts often find themselves better positioned to access institutional resources and cross-disciplinary opportunities. They are also more likely to find mentors, form research consortia, and gain exposure to cutting-edge developments outside of their immediate academic circles.

In the context of science communication, collaboration is indispensable. Translating complex scientific findings into accessible and engaging content for non-specialist audiences requires input from diverse professionals, including scientists, educators, journalists, and digital media experts. Bridging the gap between academic research and public understanding requires fostering interdisciplinary partnerships that merge technical expertise with storytelling, design, and audience engagement strategies (Trench 2023).

The digital era has broadened this landscape. Academic social platforms such as ResearchGate and LinkedIn have become vital spaces for exchanging ideas and building networks across borders. They enable researchers to share publications, receive feedback, and connect with potential collaborators across disciplines and continents. By leveraging digital connectivity, researchers can now extend their influence far beyond their institutions and participate in global conversations about science and society (Fährnich 2021). Digital platforms allow for more targeted communication strategies and facilitate interactions with diverse audiences. The ability to tailor content and connect with stakeholders in real time can significantly enhance the effectiveness of outreach efforts. Podcasts, webinars, virtual workshops, and social media campaigns are all part of a growing toolkit that can help researchers build relationships with communities, educators, and policymakers alike (Trench 2023).

In the life sciences, networking is particularly critical. The problems we face – biodiversity loss, climate change, emerging diseases – are too complex for any one institution or discipline to solve alone. Progress depends on what Gubbins & Dooley (2013) describe as “knowledge-generating networks,” where tools, data, methods, and insights are openly shared. These networks deliver clear synergies, but they also evolve, presenting new opportunities and new barriers at different stages. Navigating these shifts requires trust, adaptability, and sustained commitment.

Equally important is who gets to be part of these networks. Academic conferences, often the gateways to such opportunities, can be intimidating or exclusionary to researchers from underrepresented backgrounds. Implicit bias, lack of representation, and restricted access to established circles can reinforce inequities (Dennissen et al. 2019). Changing this requires intention: mentorship programs, inclusive event design, and policies that place diversity at the core of leadership and participation. The entire academic ecosystem benefits when underrepresented voices are welcomed and supported: innovation expands, perspectives deepen, and the culture of science grows more just (Posselt 2020).

Conclusion

Networking in academia – especially in outreach and science communication – is not an optional extra. It is the ecosystem through which ideas, people, and opportunities connect. When tended with care, these networks do more than amplify research – they create communities of practice that are collaborative, inclusive, and resilient. They make science visible and accessible, and they keep it accountable to the societies it serves. Educational outreach shows this power vividly. A child who bands a bird, counts pollinators, or maps a wetland is not simply “helping with data collection”, they are stepping into the role of biodiversity ambassador. They carry that experience, and the sense of stewardship it builds, into the rest of their lives. Teacher education students, who explore sustainability topics from a subject-didactic perspective, serve as advocates and multipliers in these areas, as they will be teaching future generations of young people. As science communication becomes more participatory, more digital, and more immediate, the ability to form and sustain authentic connections will decide how well we serve both science and society. The future of biodiversity conservation will belong to those who see networking not as a strategy, but as a responsibility – to each other, to the public, and to the living world we study, echoing the vision of the Kunming-Montreal Global Biodiversity Framework¹³ to foster inclusive, participatory, and society-wide action for nature.

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¹³ <https://www.cbd.int/gbf>

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Haben wir, was wir brauchen? Biodiversitätswissen in Österreich – eine Zustandsanalyse

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Der globale Verlust an Biodiversität geht mit einem ebenso gravierenden Rückgang des Biodiversitätswissens einher. Dieses umfasst sowohl die Fähigkeit zur Identifikation von Arten als auch das Verständnis zentraler ökologischer Prozesse und Funktionen von Ökosystemen. Der Mangel an gesellschaftlichem Wissen über Biodiversität untergräbt die Akzeptanz und Umsetzung notwendiger Schutz-, Erhaltungs- und Renaturierungsmaßnahmen und verstärkt damit die Dynamik des Biodiversitätsverlusts. Dieser Wissensverlust ist eng mit tiefgreifenden Veränderungen menschlicher Lebenswelten verknüpft. Urbanisierung, naturferne Erwerbsstrukturen sowie die zunehmende Entkopplung von naturbasierten Produktionsprozessen reduzieren direkte Naturerfahrungen erheblich. Gleichzeitig sind entsprechende Bildungsangebote im formalen Bildungssystem rückläufig, wodurch Erfahrungsräume und Möglichkeiten zum Verständnis ökologischer Komplexität verloren gehen. Verstärkt wird diese Entwicklung durch mediale Vermittlungsformen, die Natur häufig vereinfachen oder verzerren und eine primär hedonistische Auseinandersetzung fördern.

Vor diesem Hintergrund kommt den Universitäten als Spitze des Bildungssystems – gewissermaßen als oberste Ebene einer bildungspolitischen „Pyramide“ – eine zentrale Rolle zu. Sie sind nicht nur für die Generierung neuen Wissens verantwortlich, sondern insbesondere für die Ausbildung der Fachkräfte, die Biodiversitätswissen in andere Bildungsbereiche und in die Gesellschaft hineintragen. Dennoch zeigen sich gerade hier erhebliche Defizite: eine unzureichende Verankerung entsprechender Inhalte in Forschung und Lehre, eine fortschreitende Reduktion curricularer Umfänge, sowie strukturelle und finanzielle Engpässe, die sowohl die Einbindung externer Expertise als auch praxisorientierte Lehrformate, insbesondere Freilandlehre, erschweren. Angesichts eines zugleich wachsenden fachlichen Spektrums ist eine qualitativ hochwertige Ausbildung nur dann realistisch, wenn ausreichend Zeit für fachwissenschaftliche Grundlagen, fachdidaktische Qualifizierung und erfahrungsbasierte Lernformate zur Verfügung steht. Die derzeit zu beobachtende Verkürzung und inhaltliche Ausdünnung der Lehramtsausbildung im Bereich Biologie und Umweltbildung in Österreich steht diesem Anspruch entgegen. Zusammenfassend lässt sich festhalten, dass diese Entwicklungen nicht zwangsläufig sind, sondern das Ergebnis bildungspolitischer Entscheidungen darstellen. Soll Biodiversitätswissen als zentrale gesellschaftliche Schlüsselkompetenz erhalten und gestärkt werden, bedarf es eines klaren politischen Bekenntnisses. Um dem fortschreitenden Verlust biodiversitätsbezogenen Wissens wirksam entgegenzusteuern, ist eine strukturelle und budgetäre Stärkung der universitären Lehramtsausbildung notwendig. Ein zentraler Schritt ist die Wiedereinführung von „Biologie und Umweltbildung“ als eigenständiges Lehramtsfach sowie dessen Ausgestaltung durch ein zeitgemäß erweitertes Curriculum, das den aktuellen Herausforderungen des Biodiversitätsverlusts und einer nachhaltigen Entwicklung Rechnung trägt.

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The global loss of biodiversity is accompanied by an equally severe decline in biodiversity knowledge. This encompasses both the ability to identify species and an understanding of key ecological processes and ecosystem functions. A lack of societal biodiversity knowledge undermines the acceptance and implementation of necessary protection, conservation, and restoration measures, thereby reinforcing the dynamics of biodiversity loss. This erosion of knowledge is closely linked to profound changes in human living environments. Urbanization, forms of employment removed from nature, and the increasing decoupling from nature-based production processes greatly reduce direct experiences of nature.

At the same time, relevant educational offerings within the formal education system are in decline, leading to a loss of opportunities for experiential learning and for understanding ecological complexity. This trend is amplified by media formats that often simplify or distort nature and promote a primarily hedonistic engagement with it.

Against this backdrop, universities – as the pinnacle of the education system, indeed the top level of an educational policy “pyramid” – play a central role. They are responsible not only for generating new knowledge, but especially for training the professionals who will carry biodiversity knowledge into other educational sectors and into society. Yet significant deficits are evident precisely here: an inadequate integration of relevant content in research and teaching; a continuing reduction in curricular scope; and structural and financial constraints that hinder both the inclusion of external expertise and practice-oriented teaching formats, especially field-based instruction. Given a simultaneously expanding disciplinary spectrum, high-quality training is realistic only if sufficient time is available for disciplinary foundations, subject-specific didactics, and experiential learning formats. In Austria, the currently observable shortening and content dilution of teacher education in biology and environmental education runs counter to this requirement. In sum, these developments are not inevitable; they are the result of education policy decisions. If biodiversity knowledge is to be preserved and strengthened as a central societal key competence, a clear political commitment is needed. To effectively counter the ongoing loss of biodiversity-related knowledge, a structural and financial strengthening of university-based teacher education is essential. A key measure is the re-establishment of “Biology and Environmental Education” as a standalone teacher-training subject, supported by a modernized and broadened curriculum that reflects contemporary biodiversity and sustainability challenges.

Keywords: education system, biodiversity knowledge, biological education, field teaching, teacher training, nature experience.

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Einleitung

Der Verlust der biologischen Vielfalt ist eines der dringlichsten Probleme unserer Zeit (IPBES 2019). Grundsätzlich wird unter dem Begriff Biodiversität die Vielfalt des Lebens auf der Ebene der Gene, der Art und der Ökosysteme verstanden (United Nations 1992; Audrin 2023). Der Verlust von Biodiversität hat weitreichende Folgen auch für die Menschheit. Grundlegende Bedürfnisse wie Ernährungssicherheit, Schutz vor Naturgefahren, ökonomische Sicherheit und das individuelle Erleben von Naturverbundenheit, welches gesundheitliches Wohlbefinden fördert, werden zunehmend eingeschränkt (Heikkilä et al. 2026). Wissen über Biodiversität und ökologische Zusammenhänge zählt vermutlich zu den ursprünglichsten Wissensgebieten der Menschheit. Bereits frühe menschliche Gesellschaften waren auf detaillierte Kenntnisse über Organismen und ihre Interaktionen angewiesen, um ihr Überleben zu sichern. Biodiversitätswissen ist ein unverzichtbarer Bestandteil menschlicher Kultur (Wilson 1984; Nazarea 2006) und bildet eine wesentliche Grundlage für verantwortungsvolle und naturverträgliche Entscheidungsprozesse – sowohl auf individueller als auch auf gesellschaftlicher Ebene. In modernen, v. a. urbanen Gesellschaften sind die Möglichkeiten, Biodiversitätswissen durch direkte Naturerfahrungen zu erwerben, deutlich zurückgegangen. Eine Studie, die 2019 in Dänemark durchgeführt wurde, macht deutlich, dass nur 35 % der Kinder (9–10 Jahre, $n = 602$) häufige einheimische Tierarten kennen (Hooykaas et al. 2019). In einer Studie zur Vogelartenkenntnis von Erwachsenen in Bayern erkannten die jüngeren Untersuchungsteilnehmer:innen deutlich weniger Arten als die über 60-jährigen. Durchschnittlich wurden nur sechs von den 15 abgefragten Vogelarten richtig bestimmt. 4,5 % der befragten Personen konnten keine einzige Art richtig bestimmen und nur 0,5 % der Untersuchungsteilnehmer:innen erkannten alle Arten. Diese Studie zeigte auch einen Zusammenhang zwischen Wissen und der Bereitschaft, sich für den Naturschutz einzusetzen, auf (Enzensberger et al. 2022).

Der schwindende direkte Kontakt mit der Natur (*“extinction of experience”*; Pyle 1993), wird durch Urbanisierung, veränderte Freizeitgewohnheiten, fortschreitende Digitalisierung und strukturelle Veränderungen der Arbeitswelt verstärkt. Daher ist der zunehmende Verlust dieses Wissens nicht nur ein ökologisches, sondern auch ein gesellschaftliches Problem. Fehlende positive Naturerfahrungen führen dazu, dass die Natur immer seltener bewusst wahrgenommen, wertgeschätzt und schließlich auch geschützt wird. Dieser Verlust an Erfahrung entwickelt sich zu einem sich selbst verstärkenden Kreislauf: Ohne Naturerlebnisse sinkt das Interesse an Natur, wodurch entsprechende Erfahrungen weder gesucht noch gesellschaftlich eingefordert werden. Die Konsequenzen dieses Prozesses kommen in der Redensart, „Was man nicht kennt, liebt man nicht, und was man nicht liebt, schützt man nicht“, zum Ausdruck (*“What is not known will not be loved, and what is not loved will not be conserved”*; Pyle 1993; Liefänder & Bogner 2016). Bereits Aldo Leopold betonte die zentrale Rolle von Bildung für die Entwicklung einer ökologischen Ethik. Er argumentierte, dass ethisches Handeln gegenüber der Natur nur dann möglich sei, wenn Menschen lernen, natürliche Zusammenhänge wahrzunehmen, zu verstehen und wertzuschätzen (Leopold 1949; Dicks 2014). Demgegenüber zeigen Studien, dass eine starke Verbundenheit mit der Natur Verhaltensweisen fördert, die zum Schutz der Natur und zum Erhalt von Artenvielfalt beitragen. Maßnahmen, die die sichtbare Biodiversität z. B. in Wohngebieten fördern, wie das Anpflanzen artenreichen Blumenwiesen oder Hecken, die Lebensräume für unterschiedliche Insekten oder Vogelarten bieten, fördern die individuelle Naturwahrnehmung

und damit die Naturverbundenheit, was wiederum dazu beiträgt, dass sich Menschen eher für den Erhalt von Biodiversitätsflächen einsetzen (Hamlin & Richards 2022).

Bildung spielt eine entscheidende Rolle bei der Verbesserung von Biodiversitätskompetenz. Durch die Integration multidisziplinärer Ansätze verbunden mit lokalem Wissen in die Schul- und Hochschullehrpläne kann Biodiversitätskompetenz sowie Naturverbundenheit und Naturschutzverhalten von Schüler:innen und Studierenden und damit von künftigen Generationen gefördert werden. Gerade in diesem Kontext ist ein ganzheitlicher und integrierter Bildungsansatz, der digitale Medien und praktische Erfahrungen sowie lokales Wissen einbezieht empfehlenswert (Fajri et al. 2025).

Nur durch gezielte, erfahrungsbasierte Umwelt- und Biodiversitätsbildung lässt sich der Verlust des Bezugs zur Natur langfristig aufhalten und Biodiversitätswissen als kulturelle Ressource bewahren. Obwohl die Problematik seit Jahrzehnten bekannt ist, nehmen Maßnahmen gegen die Naturentfremdung im Bildungsbereich ab. Können Lehrende selbst nicht auf fundiertes Biodiversitätswissen und eigene positive Naturerfahrungen zurückgreifen, sind sie kaum in der Lage, solche Erfahrungen zu vermitteln. Als Folge bleiben diese Erfahrungen großen Teilen der Gesellschaft verwehrt: Eine Studie zur Artenkenntnis zukünftiger Biologie- und Sachunterrichtslehrkräfte zum Ökosystem Wattenmeer zeigt den geringen Wissensstand der zukünftigen Lehrenden auf (Schmäing & Grotjohann 2023). Besonders besorgniserregend ist, dass dieser Prozess zunehmend auch den tertiären Bildungsbereich betrifft. Dort wiegt der Verlust des Bezugs zur und des Verständnisses von Natur besonders schwer, weil das Bildungspotenzial einer Gesellschaft maßgeblich von der qualitativ hochwertigen Ausbildung zukünftiger Entscheidungsträger:innen und Lehrender abhängt.

Obwohl Biodiversitätswissen eine zentrale kulturelle Ressource der Menschheit ist, nehmen sowohl die Möglichkeiten, es zu erwerben, als auch die institutionellen Kapazitäten, es weiterzugeben, kontinuierlich ab. Dieser Prozess ist vielschichtig und lässt sich auf mehrere, miteinander verflochtene strukturelle Entwicklungen zurückführen. Die Beiträge und Inhalte bei den „Tagen der Biodiversität 2025“ (BOKU University, Wien; 25.-28. Februar 2025) zum Thema Biodiversitätsbildung lieferten die Basis für diesen Artikel und werden, mit besonderem Fokus auf die Entwicklung in Österreich, im Folgenden dargestellt.

Fehlender Zugang zur Natur

Aufgrund fortschreitender Eingriffe in und Zerstörung der Natur ist es in großen Teilen der Welt unmöglich geworden, Natur und Biodiversität ohne direkten oder indirekten menschlichen Einfluss wahrzunehmen. Es gibt weltweit fast keine Naturräume mehr, die als Referenzräume dienen könnten, um unberührte biologische Vielfalt und ursprüngliche ökologische Zusammenhänge unmittelbar zu erleben und zu erlernen. Auch zu naturnahen Lebensräumen ist der Zugang für die Mehrheit der Menschen häufig mit finanziellen, sozialen oder infrastrukturellen Kosten verbunden, wodurch intensive Naturerfahrungen zunehmend einer privilegierten gesellschaftlichen Schicht vorbehalten bleiben. Folglich fehlt in weiten Teilen der Gesellschaft die Möglichkeit, intensive Naturerfahrungen zu machen und eine Kultur der Naturerfahrung zu entwickeln („knowledge extinction“, „extinction of experience“, „shifting baseline“-Phänomen, Verschiebung von Bezugsgrößen; Papworth et al. (2009); Soga & Gaston (2016, 2020, 2025)).

Nanglu et al. (2023) beschreiben sehr treffend, wie auch die wissenschaftliche Gemeinschaft zunehmend vom Verlust direkter Naturerfahrungen betroffen ist, wodurch ihr Potenzial eingeschränkt wird, zentrale Forschungs-, Ausbildungs- und Vermittlungsaufgaben im und für den tertiären Bildungsbereich wahrzunehmen. Wesentliche Triebkräfte dieser Entwicklung sind tiefgreifende Veränderungen der globalen Forschungslandschaft, die aus ökonomischen, sozialen und umweltbezogenen Zwängen sowie aus technischen und kulturellen Innovationen resultieren (siehe Abb. 2 in Nanglu et al. 2023). Diese Veränderungen führen nicht nur zu einem Verlust an Möglichkeiten, direkte Freilandforschung durchzuführen, bzw. taxonomische Erfahrungen zu sammeln, sondern auch zu einer Erosion der fachlichen Kompetenzen und der Motivation zu dieser Forschung.

Selbstverstärkender Verlust des Bezugs zur Natur schwächt die Fähigkeit, Biodiversitätswissen zu erlangen und biodiversitätsförderndes Verhalten zu entwickeln

Gesellschaftliche Entwicklungen führ(t)en zu einem Verlust der Fähigkeiten, die notwendig sind, um Biodiversitätswissen zu erlangen, zu nutzen und weiterzugeben. Insbesondere die Entwicklungen des Internets und der dort verfügbaren konsumierbaren Inhalte verändern die kognitiven Kapazitäten und scheinen zu einer Fokussierung auf kurzlebige und schnell wechselnde Ereignisse hinzuwirken. Auch wenn noch nicht vollständig geklärt ist, welchen Einfluss das Internet grosso modo auf die kognitiven Fähigkeiten der Menschheit hat und haben wird, ist doch von einer eher negativen Wirkung auf den Erwerb von Wissen und im besonderen Biodiversitätswissen auszugehen. Die Kulturtechnik der Naturbeobachtung als direktes Mittel zur Naturerfahrung und die Fähigkeit zur Immersion in einen Lebensraum (Lim et al. 2020) werden damit nicht trainiert. Auch wenn manche Formate, wie zum Beispiel Artbestimmungs-Apps, zu einer Beschäftigung mit der Natur oder der Biodiversität führen können, bieten diese oft einen oberflächlichen Zugang. Biodiversitäts-förderliche Inhalte, die z. B. eine Einschätzung der Auswirkungen des eigenen oder fremden Verhaltens auf Biodiversität und Natur ermöglichen, sind wenig nachgefragt und haben im Vergleich zu Formaten, die höheres Potenzial zur Identifikation, Interaktion, Unterhaltung und Eskapismus bieten, geringere Reichweiten.

Aus dem Zusammenspiel dieser Problemfelder entsteht ein gesellschaftlich potenziell bedrohlicher Sachverhalt, nämlich die mangelhafte Fähigkeit der Einzelnen, Konsequenzen der Biodiversitätskrise und der Klimakrise zu erkennen. Damit wird die Wahrscheinlichkeit, biodiversitätsförderndes Verhalten zu entwickeln, herabgesetzt – dies betrifft neben den individuellen Entscheidungen auch die Teilhabe an demokratischen Prozessen und anderen kollektiven Praktiken.

Einschränkung wissenschaftlicher und edukativer Kompetenz

Insbesondere die Abnahme taxonomischer Expertise und freilandbasierter Forschungskompetenzen verdeutlicht diese Entwicklung. Der Rückgang entsprechender Expertise bewirkt einen Mangel an wissenschaftlicher und edukativer Kompetenz zur Erforschung biologischer Vielfalt sowie zur fundierten Vermittlung ihres ökologischen, kulturellen und gesellschaftlichen Werts (Godfray 2002). Dies wird nochmals verstärkt, da das Engagement in der Lehre bei der Beurteilung von Karriereleistungen der Wissenschaftler:innen an einigen

Universitäten immer weniger berücksichtigt wird. Es ist daher jetzt schon zu beobachten, dass hoch spezialisiertes, personalisiertes Biodiversitätswissen als zentrale Kulturtechnik auf akademischem Niveau zunehmend verloren geht. Dieser Prozess wird in der Literatur unter anderem im Zusammenhang mit dem Rückgang taxonomischer Fachkompetenz und der sogenannten „Red List of Taxonomists“ diskutiert (Hochkirch et al. 2022). Diese Entwicklung wird auch nur geringfügig durch Initiativen zur Natur- und Biodiversitätsvermittlung außerhalb formaler Bildungsinstitutionen gebremst.

Akademische und bildungspolitische Strukturprobleme

Eine zentrale Ursache dafür, dass die Möglichkeit, Biodiversitätsexpertise aufzubauen und dieses Wissen langfristig im Bildungssystem zu verankern, verloren gegangen ist, liegt in der Veränderung akademischer Strukturen: biodiversitätsbezogenes Wissen – insbesondere Artenkenntnis, Freiland Erfahrung und ökologische Kompetenz – hat gegenüber stärker technologischen oder modellbasierten Fähigkeiten an Bedeutung verloren. Dieser Prozess wird in der Fachliteratur als *taxonomic impediment* beschrieben und bezeichnet die systematische Unterbewertung taxonomischer Expertise trotz ihrer grundlegenden Bedeutung für Biodiversitätsforschung und -schutz (Hoagland 1996).

In Österreich ist diese folgenreiche Entwicklung jedoch weniger in Veränderungen akademischer Praxis zu verorten als vielmehr in bildungspolitischen Entscheidungen. Wie erneut im Barometer der Biodiversität des Österreichischen Biodiversitätsrats (Kernforderung 4: Wissenschaft und Bildung stärken) festgestellt (Österreichischer Biodiversitätsrat 2026), sind in der österreichischen Forschungs- und Bildungspolitik in den Bereichen Biodiversitätsforschung, -lehre und -bildung keine Fortschritte erkennbar und bezüglich der in den Kernforderungen genannten Punkte fehlt es der Politik an Problembewusstsein und Umsetzungswillen. Speziell im tertiären Bildungssektor manifestieren sich verschiedene Aspekte des Verlustes von Biodiversitätswissen in der Stellenbesetzungskultur an Hochschulen, im mangelnden Angebot von Biodiversitätswissen in vermeintlich technischen oder angewandten Studiengängen sowie in der Biodiversitätslehre selbst. Stellenbesetzungen an Hochschulen werden *lege artis* besonders nach Maßzahlen der wissenschaftlichen Produktivität in hochkompetitiven Bereichen, aber weniger nach Gesichtspunkten der fachlichen Landschaft getroffen. Dadurch entsteht ein Anpassungsprozess, der eine Hinwendung zu aktuellen Mainstream-Themen und Methoden bedeutet. Dieser Trend wird verstärkt durch fehlende Förderschienen, da wichtige biologische Fragen in nicht-mainstream-Hypothesengetriebenen Projekten behandelt werden. Diese liefern jedoch ebenso innovative wie auch gesellschaftlich relevante Ergebnisse und Datengrundlagen, z. B. hinsichtlich Entwicklungstrends zu Verbreitung und genetischer Diversität oder zu Neobiota.

Dadurch ergibt sich das Risiko, spezialisiertes Biodiversitätswissen nicht mehr in der Hochschullandschaft abzubilden, was sich auf alle darunterliegenden Ebenen der Bildungslandschaft auswirkt. Während zum Beispiel die Biodiversität von Fischen und eines Gutteils der Säugetiere und Vögel an mehreren österreichischen Universitäten fachlich und curricular verankert sind, bleiben viele Gruppen der Wirbellosen außen vor. Im Zusammenhang mit dem stärker werdenden Fokus auf einzelne Organismengruppen von juristischer Bedeutung (zum Beispiel Arten der Vogelschutz- und Fauna-Flora-Habitat-Richtlinie (2009/147/EG; 92/43/EWG), auf Bestäuber oder auf biologische Qualitätselemente der Wasserrahmenrichtlinie

(2000/60/EG)) führt dies zu einer fachlichen Verarmung der Hochschullandschaft. Diese wird durch den ökonomischen Zwang zur Austerität befördert, der im Übrigen auch für eine Schlechterstellung des Biodiversitätswissens in angewandten und technischen Studiengängen sorgt. So umfasst das Bachelor-Curriculum Umweltingenieurwissenschaften der Universität für Bodenkultur Wien lediglich 4 ECTS an Lehrveranstaltungen, die Biodiversitätswissen anbieten; das Landschaftsplanung- und Landschaftsarchitekturstudium ebendort bietet zwar 10 ECTS an Lehrveranstaltungen mit Bezug zur Biodiversität an, aber lediglich 4 ECTS davon mit einem expliziten Fokus auf die Biodiversität von Wirbellosen. Aber auch ein Studium der reinen Grundlagenfächer ist keine sichere Bastion des Biodiversitätswissens; auch in diesem Fall bedarf es zusätzlicher, zum Teil extra-curriculärer Anstrengungen der Studierenden, wie des Tierökologiezertifikats (<https://www.uibk.ac.at/de/ecology/tieroekologie-zertifikat/>), des Österreichischen Freilandbotanik-Zertifikats (Freilandbotanik-Zertifikat – Universität Innsbruck) oder der Feldmykolog:innen-Ausbildung (<https://www.dgfm-ev.de/de/fortbildung/feldmykolog-innen>), um Biodiversitätswissen zu erreichen. Auch wenn ein Nadir der Biodiversitätsvermittlung bislang nicht erreicht scheint, ist das Fehlen eines grundsätzlichen Bekenntnisses zur qualitätsvollen Biodiversitätslehre evident, was wiederum zur Schwächung entsprechender Forschungsfelder führt.

Dieser Mangel findet seinen Ausdruck zudem in der Reduktion der Lehrbudgets, mit denen personelle Einschränkungen der Universitäten ausgeglichen oder Freilandlehrveranstaltungen finanziert werden können. Dies betrifft grundsätzlich alle Studierende biologischer Fächer, sei es Bachelor, Master oder Lehramtsstudium. In letzterem haben die sukzessiven Kürzungen der Lehramtsausbildung für Biologie und Umweltkunde infolge des neuen Universitätsgesetzes zu einem weiteren Abbau der gesellschaftlichen Kompetenz, Biodiversitätswissen zu vermitteln, geführt. Während der Umfang der zu vermittelnden Inhalte in Biologie und Umweltkunde kontinuierlich zugenommen hat – etwa durch neue Erkenntnisse in Molekularbiologie, Ökologie, Klimawissenschaften, Biodiversitätsforschung, Umweltethik und Bildung für nachhaltige Entwicklung – wurde und wird die Ausbildungszeit für Lehramtsstudierende gleichzeitig verkürzt und das Curriculum verdichtet. Außeruniversitäre Bildungseinrichtungen und Fachvereine können Defizite in der Ausbildung höchstens etwas abfedern, sind jedoch unterfinanziert. Zusätzlich wurde das von sogenannten „externen“ Spezialist:innen an Universitäten bereitgestellte Lehrangebot, beziehungsweise deren Beteiligung an Lehrveranstaltungen aufgrund von Sparmaßnahmen kontinuierlich abgebaut. Der Verlust notwendiger Expertise ist heute oft außerhalb der Universitäten gegeben, sie nicht zu nutzen, wirkt sich langfristig aus.

Die Reduktion und inhaltliche Verschlankung der Curricula führten zu einer deutlichen Schwächung der akademischen Ausbildung im Bereich der Biodiversität (Gereben-Krenn et al. 2024). In der Konsequenz ergibt sich daraus, dass gerade jene Ausbildungsleistungen, die für den Erhalt und die Weitergabe von Biodiversitätswissen von zentraler gesellschaftlicher Bedeutung sind, zurückgefahren werden. Diese Entwicklung ist nicht als unbeabsichtigte Nebenwirkung, sondern als direkte Konsequenz bildungspolitischer Prioritätensetzungen zu verstehen. Die Ausrichtung von Lehrstühlen, der Abbau von Personalstellen, die Reduktion der Studiendauer und die Verschlankung von Lehrplänen erfolgten vor dem Hintergrund kurzfristiger Einsparungsziele, ohne die langfristigen Folgen für Bildungsqualität und gesellschaftliche Naturbeziehung ausreichend zu berücksichtigen.

Nur wenn die genannten Problemfelder behoben werden, lässt sich die Erosion des Biodiversitätswissens stoppen und der für die Erhaltung unserer Lebenswelt notwendige politische und gesellschaftliche Konsens herstellen.

Unzureichende Ausbildung der Lehrenden – eine Folge der Abwärtsspirale

Curricular bedingte Defizite und Kürzungen in der Lehrkräftebildung wirken sich unmittelbar auf die Qualität der Biodiversitätsvermittlung aus und verstärken langfristig den Verlust biodiversitätsbezogener Kompetenz in der Gesellschaft (Schmäing & Grotjohann 2023). Das Fehlen eines grundsätzlichen Bekenntnisses zur qualitätsvollen Biodiversitätslehre erklärt auch die sukzessiven Kürzungen der Lehramtsausbildung für das Unterrichtsfach Biologie und Umweltbildung. Dies soll im Folgenden näher erläutert werden.

Die Ausbildung von Studierenden im Unterrichtsfach „Biologie und Umweltbildung“ wurde über Jahre hinweg systematisch zurückgefahren. Besonders problematisch ist in diesem Zusammenhang die schrittweise Abkehr vom Lehramtsstudium „Biologie und Umweltbildung“ als eigenständigem Fachstudium. Ab dem Jahr 2001 musste auch dieses Lehramtsstudium mit einem weiteren Unterrichtsfach kombiniert werden und ist seither nicht mehr als Einzelfach studierbar, was die erste deutliche Kürzung dieses Studiums war. 2015 wurden alle Lehramtsstudien der Bologna-Studienstruktur unterworfen und in ein Bachelor-Masterstudium für die Sekundarstufe 1 und 2 umgewandelt. Dies führte, gerade in den biologischen Disziplinen, zu einer weiteren starken Kürzung der Inhalte. Unter dem Titel Pädagog:innenbildung NEU beginnen nun im Wintersemester 2026/27 Lehramtsstudien, die weitere Kürzungen erfahren mussten. Als Hauptbegründung für die letzte Einkürzung diente der Mangel an Lehrer:innen an den Schulen.

Während der Umfang der zu vermittelnden Inhalte im Lehramtsstudium „Biologie und Umweltbildung“ in diesen 25 Jahren kontinuierlich zugenommen hat – etwa durch neue Erkenntnisse in Molekularbiologie, Ökologie, Klimawissenschaften, Biodiversitätsforschung, Umweltethik und Bildung für nachhaltige Entwicklung – wurde dem durch einen entsprechenden Ausbau des Curriculums für Lehramtsstudierende nicht Rechnung getragen. Im Gegenteil, die vier Säulen der Lehramtsstudiums, fachwissenschaftliche, fachdidaktische, pädagogische und schulpraktische Bildung müssen quasi um die vorgegebenen Semesterwochenstunden konkurrieren. Abbildung 1 illustriert dieses Missverhältnis in Form einer Grafik zu einem Gesetzesentwurf, der die Reduktion der Lehramtsausbildung in Österreich um ein Jahr vorsah. Diese Änderung wurde umgesetzt und greift mit 1. Oktober 2026 (Abb. 1).

Wesentliche Inhalte aus fachwissenschaftlicher und fachdidaktischer Sicht können in Zukunft ob der vorgegebenen Studienarchitektur schlichtweg nicht mehr durchgenommen werden. Biodiversitätsbezogene Kompetenzen – insbesondere Artenkenntnis, Systematik, Lebensraumkenntnisse und Freiland Erfahrung – zählen dabei zu den ersten Bereichen, die dem Rotstift zum Opfer fallen, da sie als aufwendig, kostenintensiv und als schwer standardisierbar gelten. Diese Serie an Verkürzungen des Lehramtsstudiums „Biologie und Umweltbildung“ steht in einem eklatanten Widerspruch zur stetig wachsenden Bedeutung

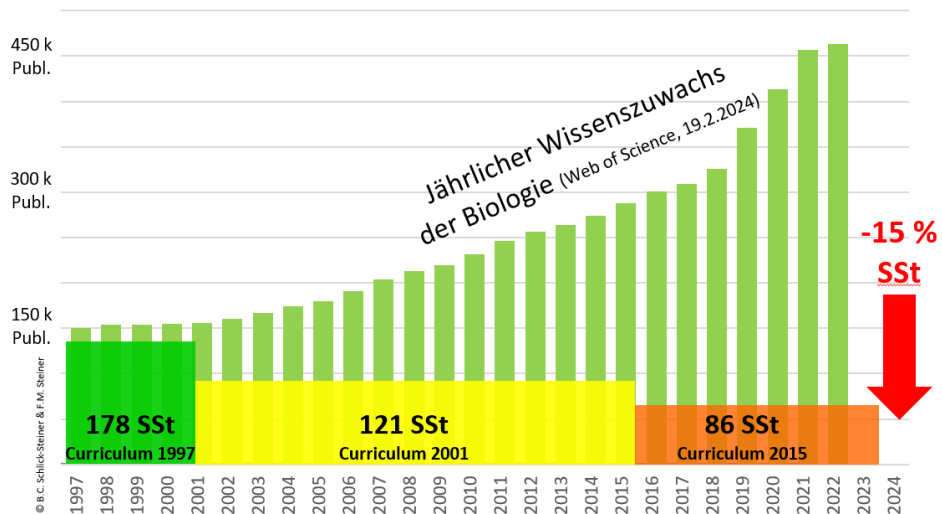


Abb. 1: Die Graphik aus einer Stellungnahme zu einem Gesetzesentwurf bezüglich der Verkürzung der Lehramtsausbildung in Österreich um ein Jahr. Verhältnis zwischen jährlichem Wissenszuwachs in der Biologie und dem Umfang (in Semesterwochenstunden) der Fach- und Fachdidaktik-Ausbildung im Fach „Biologie & Umweltkunde“ an der Universität Innsbruck, von 1997 bis 2024. Methodik: Quantifizierung des jährlichen Wissenszuwachses in k (=1000) Publikationen nach der Methode in Steiner et al. (2015): Systematic Biology 64: 860-868: Abfrage Web of Science vom 19.2.2024 (Anzahl der Publikationen für 2023 über Web of Science noch nicht komplett zugänglich). Curricula 1997 und 2001: Diplomstudium (Abschluss Mag.), Curriculum 2015: Bachelor- und Masterstudium zusammengezählt (Abschlüsse BSc. und MSc.). Im Gesetzesentwurf geplante Verkürzung der Ausbildung um ein Studienjahr symbolisch mit rotem Pfeil dargestellt. | **Fig. 1:** Graphic from a statement on a draft law proposing to shorten teacher education in Austria by one year. Relationship between the annual increase in biological knowledge and the scope (in semester hours per week) of subject-specific and subject-didactic training in “Biology & Environmental Studies” at the University of Innsbruck from 1997 to 2024. Methodology: Quantification of the annual increase in knowledge in k (=1000) publications following the method of Steiner et al. (2015). Web of Science query (dated 19 February 2024; the number of publications for 2023 is not yet fully accessible via Web of Science). Curricula 1997 and 2001: diploma program (degree: Mag.). Curriculum 2015: combined Bachelor’s and Master’s program (degrees: BSc and MSc). The reduction of the program by one academic year proposed in the draft law is symbolically indicated by a red arrow.

der Biologie in verschiedensten gesellschaftlichen Aspekten. Die Reduktion fachwissenschaftlicher und freilandbasierter Ausbildungsteile hat zur Folge, dass Absolvent:innen zwar formal qualifiziert sind, jedoch häufig nicht mehr über jene tiefgehenden Fachkenntnisse verfügen, die für eine qualitätsvolle Vermittlung der Lehrinhalte erforderlich wären (siehe auch Irwin 2026). Diese Diskrepanz zwischen steigenden Lehrinhalten und reduzierter Ausbildung, hat zu einer strukturellen Überforderung in der Lehrer:innenbildung geführt: Immer mehr Inhalte sollen in immer kürzerer Zeit vermittelt werden, ohne dass dafür entsprechende personelle oder zeitliche Ressourcen bereitgestellt werden.

All diese Überlegungen sind eingebettet in die Diskussion, welche Funktion Schule hat und welchen Bildungsbegriff wir unserem Anliegen zugrunde legen. Gerade die Bedeutung des Unterrichtsfaches „Biologie und Umweltbildung“ kann im Spannungsfeld „Ausbildung versus Bildung“ sehr unterschiedlich gesehen werden (Lacina 2026). Soll die Biologie in der Schule auf unmittelbare Nützlichkeit reduziert werden oder soll das Fach den jungen Menschen ermöglichen, die Welt besser und umfassender zu verstehen und mit ihr verantwortungsvoller umzugehen als bisher? Nur wenn die genannten Problemfelder behoben werden, lässt sich die Erosion des Biodiversitätswissens stoppen und der für die Erhaltung unserer Lebenswelt notwendige politische und gesellschaftliche Konsens herstellen.

Notwendige strukturelle Maßnahmen

Sofern der politische Wille vorhanden ist, die Abwärtsspirale zu stoppen, sollten sofort tiefgreifende und nicht durch budgetäre Prioritäten verwässerte Reformen in der Lehrer:innenbildung für allen Bildungsstufen eingeleitet werden. Dazu zählt auch eine gezielte Stärkung der außeruniversitären Biodiversitätsvermittlung in allen Facetten. Vor diesem Hintergrund ist eine grundlegende Neubewertung der verschiedenen universitären Studienrichtungen der Biologie erforderlich. Ohne starke Verankerung von Biodiversitätswissen in der universitären Lehre und Forschung – auf die sich dieser Artikel schwerpunktmäßig bezieht – kann die Qualitätssteigerung und letztlich die angestrebte gesellschaftliche Transformation nicht gelingen. Dies würde auch der Forderung entgegenkommen, dass es heute auch Aufgabe der Universitäten ist, die Naturverbundenheit der Studierenden zu stärken (Kleespies & Dierkes 2023a, 2023b, 2025).

In curricularen Überarbeitungen sollten Lehrveranstaltungen zu Biodiversität und Ökosystemen für alle Studierenden der Biologie im Bachelorstudium verpflichtend sein. Zusätzlich wären für alle Biologiestudent:innen zumindest eine Freilandlehrveranstaltung von mindestens 4 Semesterwochenstunden verpflichtend vorzusehen. Dementsprechend müssten bei Nachbesetzungen an den Universitäten Stellen ausgeschrieben werden, die klar der Forschung und Lehre der mitteleuropäischen Biodiversität gewidmet sind.

Bezugnehmend auf das in diesem Jahr nach neuem Curriculum beginnende, Lehramtsstudium für das Unterrichtsfach „Biologie und Umweltbildung“ muss aus fachwissenschaftlicher und fachdidaktischer Sicht die Forderung weiterhin aufrecht bleiben, dass dieses Unterrichtsfach wieder als eigenständiges Einzelstudium ohne Kombinationspflicht studierbar sein soll. Angesichts des breiten und weiterhin wachsenden fachlichen Spektrums ist ein qualitativ hochwertiges Studium nur dann realistisch, wenn ausreichend Studienzeit für fachwissenschaftliche Grundlagen, didaktische Ausbildung und praxisorientierte Naturerfahrung zur Verfügung steht.

Damit verbunden ist eine klare Schwerpunktsetzung auf einen deutlich erhöhten Anteil fachwissenschaftlicher Module notwendig, der jenem früherer Ausbildungsmodelle entspricht und den tatsächlichen Anforderungen des Fachs gerecht wird. Eine qualitativ hochwertige Lehrer:innenbildung im Bereich der Biodiversität erfordert Zeit für Feldarbeit, für den Erwerb von Artenkenntnis, für systematisches Denken und für die Entwicklung pädagogischer Kompetenzen zur Anleitung von Naturerfahrungen. Diese Elemente lassen sich nicht beliebig verdichten oder durch digitale Formate ersetzen.

Der fachfremde Unterricht in Schulen sowie das Unterrichten mit einem noch nicht abgeschlossenen Bachelorstudium läuft den oben beschriebenen Bildungszielen zuwider und sollte ehestens eingestellt werden. Ebenso führt ein berufsbegleitendes Masterstudium weder zur gewünschten Qualitätssteigerung noch zu einer nachhaltigen Behebung des Mangels an Lehrer:innen: Das Studieren bei gleichzeitigem Unterrichten in einer Schule – mit all den dort zu bewältigenden Problemen eines Schulalltages – ist häufig eine systematische Überforderung aller Beteiligten, der Lehrenden und Lernenden. Beiden Aufgaben kann man nur schwer gerecht werden, was in den meisten Fällen bei den Betroffenen zu erheblicher Frustration und nicht selten zum Ausstieg führt.

Zusammenfassend zeigt sich, dass der Abbau der Lehrer:innen-Bildung in biodiversitätsrelevanten Fächern das Ergebnis politischer Entscheidungen ist und auch wieder geändert werden könnte. Soll Biodiversitätswissen als gesellschaftlich relevante Schlüsselkompetenz erhalten bleiben, ist politischer Wille die Voraussetzung, dem fortschreitenden Verlust von Biodiversitätswissen wirksam entgegenzutreten.

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Evolving ABOL (the Austrian Barcode of Life Initiative): Reflections on a Decade of Coordinating a National Biodiversity Initiative

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The Austrian Barcode of Life (ABOL) initiative was founded in 2014 with the ultimate aim of systematically documenting all animal, plant, and fungal species occurring in Austria using DNA barcodes. From the beginning, the coordination of this nationwide initiative has been anchored at and spearheaded by the Natural History Museum Vienna (NHMW). For more than a decade, it has built an inter-institutional network that brings together biological collections, research institutions, authorities of protected areas, professional societies, and community scientists. ABOL therefore covers not only all aspects – from data infrastructure and basic research to applied research – but has increasingly developed into a key player in socially relevant biodiversity documentation and environmental monitoring in Austria.

This report takes stock of the organizational, infrastructural, and scientific development of the initiative during the period from 2014 to 2025. In addition to the creation of reference data for organisms from Austria, national and international networks were established, applications of DNA barcoding were implemented, and participatory formats such as the ABOL BioBlitzes were developed.

ABOL exemplifies a new form of a coordinated, integrative biodiversity research. It combines taxonomic expertise with molecular biological methods, openly accessible digital platforms, and societal participation. The outlook discusses the structural prerequisites required for ABOL to contribute in the long term to the implementation of international biodiversity goals. These include targets set by the EU Biodiversity Strategy for 2030. In doing so, ABOL can help address the global challenge of biodiversity loss.

Szucsich NU, Sonnleitner M, Ackerl F, Kargl V, Heinzl J, Hörweg C, Haring E (2026) The Evolution of ABOL (Austrian Barcode of Life): Rückblick auf ein Jahrzehnt der Koordination einer nationalen Biodiversitätsinitiative

Die Initiative „Austrian Barcode of Life“ (ABOL) wurde 2014 mit dem Ziel gegründet, alle in Österreich vorkommenden Tier-, Pflanzen- und Pilzarten systematisch mithilfe von DNA-Barcodes zu erfassen. Von Beginn an war die Koordination dieser landesweiten Initiative am Naturhistorischen Museum Wien (NHMW) angesiedelt. Die Koordination baute ein überinstitutionelles Netzwerk auf, das biologische Sammlungen, Forschungseinrichtungen, Schutzgebietsbehörden, Fachgesellschaften und engagierte Bürgerwissenschaftler:innen zusammenbringt – dieses wird seit über einem Jahrzehnt gepflegt und erweitert. ABOL deckt somit nicht nur alle Aspekte ab – von der Dateninfrastruktur und der Grundlagenforschung bis hin zur angewandten Forschung –, sondern hat sich zunehmend zu einem wichtigen Akteur für die gesellschaftlich relevante Dokumentation der Biodiversität und das Umweltmonitoring in Österreich entwickelt.

Dieser Beitrag zieht Bilanz über die organisatorische, infrastrukturelle und wissenschaftliche Entwicklung der Initiative im Zeitraum von 2014 bis 2025. Neben der Erstellung von Referenzdaten für Organismen aus Österreich wurden nationale und internationale Netzwerke aufgebaut, Anwendungen des DNA-Barcodings implementiert und partizipative Formate wie die ABOL-BioBlitze entwickelt.

ABOL ist ein Beispiel für eine neue Form koordinierter, integrativer Biodiversitätsforschung. Es vereint taxonomische Expertise mit molekularbiologischen Methoden, frei zugänglichen digitalen Plattformen und gesellschaftlicher Teilhabe. Der Ausblick erörtert die strukturellen Voraussetzungen, die ABOL benötigt, um langfristig bei der Umsetzung internationaler Biodiversitätsziele mitzuwirken. Dazu gehören die Ziele der

EU-Biodiversitätsstrategie 2030. So kann ABOL dazu beitragen, die globale Herausforderung des Biodiversitätsverlusts zu bewältigen.

Keywords: DNA barcoding, scientific collections, FAIR data, biodiversity, monitoring, data infrastructure, species identification.

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Background and external framework conditions

The systematic recording and documentation of species is a core task of biodiversity research – both in basic research and in applied fields such as nature conservation, environmental monitoring, and policy advice. In this context, the correct identification of species is of paramount importance. However, this expertise has become increasingly scarce in recent decades (Cardoso et al. 2011; Engel et al. 2021; Hochkirch et al. 2022).

Biological diversity – namely the diversity of species, their genetic diversity, and the diversity of habitats and biological communities – is severely threatened worldwide as well as in Austria (IPBES 2019; Umweltbundesamt 2025). The main drivers include land-use change, exploitation of natural resources, environmental pollution, invasive species, and climate change. This decline leads to the impairment of ecosystem functions, thereby endangering human health, economic systems, and quality of life (IPBES 2019). “Bending the curve” of global biodiversity loss thus is one of the greatest challenges of the 21st century (Leclère et al. 2020). Sound knowledge of biological diversity is a fundamental prerequisite for quantifying biodiversity loss and for data-driven implementation of measures for effective conservation efforts and sustainable use of natural resources.

Thus, an increasing demand for monitoring coincides with a decline in taxonomic expertise. In addition, the large diversity of organism groups means that rarely local experts are available for every taxonomic group. This clearly demonstrates the urgent need for new, standardized, and scalable methods for species identification and for safeguarding taxonomic experience for future generations. DNA barcoding can make a substantial contribution here and is gaining increasing importance worldwide (see Box 1 for methodological details).

Against this background, the present report reviews the developments and milestones achieved during more than a decade of operation by the Austrian Barcode of Life (ABOL) initiative. Since its foundation in 2014, ABOL has played a central role in the DNA-based identification and, more broadly, the scientific documentation of Austrian biodiversity, and has been involved in establishing the DNA barcoding approach across a wide range of applications. In addition to reviewing developmental steps and achieved milestones,

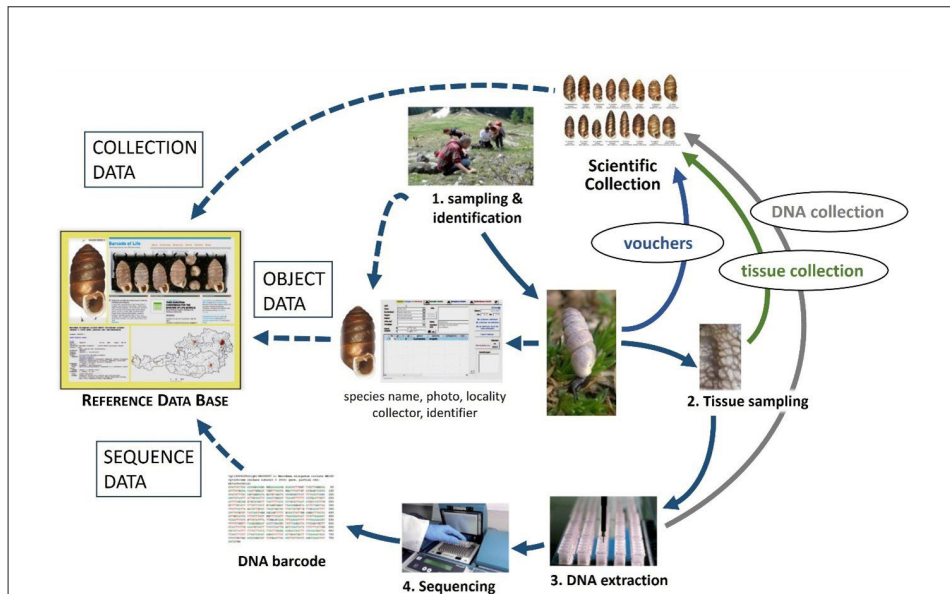
Box 1: The principle of DNA barcoding and how to establish a reference database

Fig. 1: Workflow of the generation of DNA barcode reference data. | **Abb. 1:** Arbeitsablauf zur Generierung von DNA-Barcode-Referenzdaten.

DNA barcoding is an internationally standardized method for molecular genetic species identification. It is based on specific, short DNA sequences (so-called DNA barcodes) that allow species to be distinguished and identified, and which can be PCR-amplified by fairly universal primers. A prerequisite is a reference database holding DNA barcodes from morphologically accurately identified organisms (animals, plants, or fungi). The identification of unidentified organisms is achieved by comparing sequenced DNA fragments of their genome with corresponding DNA barcodes stored in the reference database.

In animals, usually a fragment of the mitochondrial cytochrome c oxidase subunit I (COI) gene is analysed (Hebert et al. 2003). In fungi, variable regions between the nuclear rRNA genes are used as standard markers: ITS1 and ITS2 ("Internal Transcribed Spacer" 1 and 2; Schoch et al. 2012). In plants, genes of the chloroplast genome such as *rbcl* (ribulose-1,5-bisphosphate carboxylase/oxygenase large subunit), *trnL-F* (chloroplast region encompassing transfer RNAs L to F) or *matK* (maturase K), as well as nuclear markers such as ITS1 or ITS2, are employed (e.g. CBOL Plant Working Group 2009; Jones et al. 2021). For specific organism groups, numerous additional gene regions have been proposed (e.g. Alam et al. 2024).

After sequencing the DNA fragments, sequence data along with object data (i.e. all information tied directly to a voucher) and collection data is stored in a reference database (Fig. 1).

These genetic markers can be used for species identification even when organisms are morphologically difficult to identify, for example when only fragments are available (Zeale et al. 2011; Galimberti et al. 2013; Aylward et al. 2018; Esnaola et al. 2018; Naaum et al. 2018; Reeves et al. 2018; Rytönen et al. 2018; French et al. 2022) or when dealing with difficult-to-identify developmental stages (Sonet et al. 2013). DNA barcoding also enables the analysis of species composition in mixed samples (DNA metabarcoding) and the detection of traces in the environment, such as in water, soil or even in air samples (environmental DNA, eDNA). DNA barcoding has therefore become a key technology for species identification in modern biodiversity research (Kress et al. 2015), since taxonomic knowledge is not necessary for the process of species identification itself, but only for the generation of DNA barcodes. A prerequisite for widespread application of DNA barcoding is a curated, publicly accessible reference database with taxonomically validated DNA barcode sequences. The international platform BOLD (Barcode of Life Data Systems; Ratnasingham & Hebert 2007; Ratnasingham et al. 2024) provides the infrastructure for analysis, storage, quality control, and global accessibility of these data and follows the core principles of FAIR data – findable, accessible, interoperable, and reusable (Wilkinson et al. 2016).

the report examines how ABOL is structured, the role of the *ABOL Coordination*, and the position ABOL may occupy in the future within the national and international context of biodiversity research, nature conservation, and environmental policy.

The impetus for launching the ABOL initiative was not only a response to the above-mentioned requirements but also to international developments in this field. Originating in Canada (CBG – Centre for Biodiversity Genomics, University of Guelph, Ontario), DNA barcoding was already on the way of being established internationally (Hebert et al. 2003), and several national DNA barcoding initiatives had already begun their activities (NorBOL in Norway, InBio in Portugal, NBOL in the Netherlands, FinBOL in Finland, GBOL in Germany, and SwissBOL in Switzerland). In Austria, individual researchers had already generated DNA barcodes (e.g. Graf et al. 2008; Huemer et al. 2014a, b; Resch et al. 2014), but a coordinated strategy was lacking. This gap was closed with the ABOL initiative, laying the foundation for DNA-based surveys within modern biodiversity monitoring in Austria.

ABOL was launched as an open, inter-institutional initiative that now connects stakeholders from research institutions, biological collections, protected areas, authorities, professional societies, and community scientists (a term proposed as an alternative for the more widely used term “citizen scientists”; see discussion in Christian et al. 2024). The breadth of the network necessitates coverage of all aspects of DNA barcoding, from data infrastructure and taxonomic basic research to applied biodiversity monitoring and ecological research. The aim is to integrate the DNA barcoding approach into the existing biodiversity research landscape. Monitoring approaches using DNA barcoding and DNA metabarcoding (i.e. the simultaneous identification of many species within the same sample via DNA sequence comparison) are consistently understood as complementary to existing approaches, greatly expanding our capacity for species identification without replacing traditional approaches

(Hajibabaei et al. 2007; Kress et al. 2015; Martins et al. 2025). A prerequisite for the application of DNA barcoding and its integration into monitoring activities is a reference database which is as complete as possible, and which contains accurate information linking taxonomy and DNA barcodes of voucher specimens that have been accurately identified based on morphological characteristics by experts (see Box).

The period covered by this report spans the years 2014 to 2025. The focus lies on the scientific and organizational achievements of the ABOL, its strategic development, and its increasing societal relevance. Particular attention is paid to the role of the *ABOL Coordination*, which functions as a central structure for governance, quality assurance, and networking at both national and international levels.

Short history and organizational structure of the ABOL initiative

ABOL is a decentralized initiative distributed across Austria, with a central coordination unit located at the Natural History Museum Vienna (NHMW). While “ABOL” or “ABOL initiative” refers to the entire network, the “*ABOL Coordination*” – as the organizational unit – is a third-party funded project which employs a team of approximately 2.5 full-time equivalents that maintains network contacts, organizes it, and drives its future development.

Pilot phase

Preparatory work leading up to the ABOL pilot phase began already in 2010, carried out by staff members of the NHMW (Elisabeth Haring and Helmut Sattmann). An initial group of interested individuals formed during the Biodiversity Day held at the NHMW on October 21, 2010 under the title “*Land der Vielfalt – zukunftsreich?*” (translates to: Land of Diversity – rich in future?). In the following years, a project was jointly developed together with representatives of various Austrian institutions (Zimmermann et al. 2013). Thanks to funding from the Ministry of Science, a three-year ABOL pilot phase was launched in 2014 (Tab. 1, <https://www.abol.ac.at/en/about-us/#history-how-it-started>). The aim of this pilot phase was to establish methods and workflows in four groups of organisms (butterflies, molluscs, vertebrates, and parasitic worms) and to generate corresponding reference DNA barcodes. The four pilot projects were carried out at the following institutions: Tyrolean State Museums (butterflies; lead: Peter Huemer), NHMW (molluscs; lead: Anita Eschner, Luise Kruckenhauser), University of Graz (vertebrates; lead: Stephan Koblmüller), and the University of Veterinary Medicine Vienna (lead of the overall pilot phase; parasitic worms; lead: Anja Joachim). Already within the pilot phase, the *ABOL Coordination* was established at the NHMW. It was responsible for coordinating the pilot projects, network building, communication, public outreach, and the conceptual development of the overall project. The *ABOL Coordination* was supported by a steering committee consisting of nine persons from different institutions. Even during the pilot phase, DNA barcodes of Austrian organisms were generated in additional associated projects that were not funded through the ABOL pilot. Partly conceived as small DNA barcoding projects, partly embedded in larger research projects, these projects provided valuable data for ABOL’s long-term goal – a reference database for Austrian animals, plants and fungi. From its very beginning the ABOL initiative agrees upon a workflow on generating DNA barcode references, where the tissue from which DNA is extracted stems from reliably identified specimens, vouchered in

a scientific collection. An ABOL database was set up already at the very beginning of the initiative, which was intended as a working tool to support partners in data compilation and quality control as well as in the data uploading process to BOLD. The Barcode of Life Data System BOLD was ultimately chosen as the international platform where all finalised DNA barcodes are made available, allowing for applied DNA barcoding and DNA metabarcoding studies.

During the pilot phase the number of species from Austria covered in BOLD increased by almost an order of magnitude from 505 (as of July 16, 2014) to 4,241 species (as of August 29, 2017).

Main phase

For the transition from the pilot phase to a comprehensive main phase of ABOL, a project design was developed according to which DNA barcodes of at least 80% of all animal, plant, and fungal species occurring in Austria were to be generated within ten years, structured into ten taxonomic clusters (corresponding to different organism groups; Haring et al. 2015). Since a large number of the species are very rare, sometimes only recorded once in Austria, a coverage of 80% of the species was assessed as a realistic aim for a ten-years phase, based on an original estimate of 70,000 species for the fauna, flora and funga of Austria (Geiser 1998; Rabitsch & Essl 2009; Krisai-Greilhuber 2015). This goal was to be achieved with a total funding volume of approximately EUR 25 million over ten years. After accounting for institutional in-kind contributions amounting to EUR 9 million, a remaining funding requirement of approximately EUR 16 million was identified. As for this concept no global funding could be secured, an alternative approach had to be developed in which funding

Tab 1: Overview of the ABOL phases, * BMBWF – Federal Ministry of Education, Science and Research; ** BMFWF – Federal Ministry of Women, Science and Research; *** University of Veterinary Medicine Vienna | **Tab. 1:** Überblick über die ABOL-Phasen, * BMBWF – Bundesministerium für Bildung, Wissenschaft und Forschung; ** BMFWF – Bundesministerium für Frauen, Wissenschaft und Forschung; *** Veterinärmedizinische Universität Wien

Name	Duration	Funding	Budget in EUR	Funded project
Pilot phase	2014–2017	BMBWF*	499,668.33	4 pilot projects (VetMed***, NHMW, University of Graz, Tyrolean State Museums), <i>ABOL Coordination</i> (NHMW)
Main phase 1	2017–2021	BMBWF	621,200	<i>ABOL Coordination</i> project (NHMW)
Main phase 2	2021–2024	BMBWF; Universities of Vienna, Graz and BOKU Univ.	555,750 70,000	<i>ABOL Coordination</i> project (NHMW)
Main phase 3 ongoing	2024–2027	BMFWF**	798,180	<i>ABOL Coordination</i> project (NHMW)

focused on the *ABOL Coordination* alone. Data generation was not covered, but third-party funding had to be separately acquired by partner institutions, supported by the *ABOL Coordination* team. Due to the necessity to build up the reference database by a conglomerate of various projects (Haring et al. 2017), the initial time plan of ten years became unrealistic.

Financial structure of the main phase of ABOL

The main phase of ABOL started in November 2017, with funding for the *ABOL Coordination* provided by the Ministry of Science (former BMBWF, currently BMFWF; Tab. 1). After the first three-year period (ABOL I: 2017–2020), funding for the *ABOL Coordination* was subsequently extended twice, each time for a further three years. In the second phase (ABOL II: 2021–2023), additional funding contributions to the *ABOL Coordination* were provided by the University of Vienna (one year), the University of Graz (three years), and BOKU University (three years). The third ABOL phase (ABOL III: 2024–2027) is currently ongoing, again funded by the Ministry of Science.

As a conglomerate of projects serving the achievement of shared objectives, the ABOL initiative is financed through a diversified portfolio of funding sources acquired by the *ABOL Coordination* and/or its partners. While the *ABOL Coordination* is financed by the Federal Ministry of Science, various other funding schemes are used in projects of the ABOL initiatives, both for the generation of DNA barcodes as well as for applied DNA barcoding. For these projects money was acquired from federal funding schemes, such as higher education structural funds (HRSM; BMBWF, now BMFWF), the Biodiversity Fund (BMK, now BMLUK), the Austrian Science Fund (FWF), the Austrian Research Promotion Agency (FFG), as well as international schemes and EU funding programmes (WTZ,

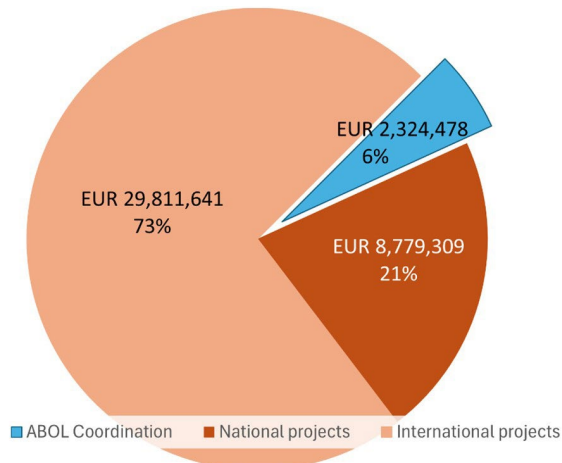


Fig. 2: Graphical representation of the leverage effect of the *ABOL Coordination* in the period 2014 to 2025. Not shown in Fig. 2 are the budgets of ABOL-associated projects from the pilot phase as well as in-kind contributions within projects. | **Abb. 2:** Grafische Darstellung des Hebeleffekts der *ABOL-Koordination* im Zeitraum von 2014 bis 2025. Nicht in Abb. 2 dargestellt sind die Budgets der Assoziierten ABOL-Projekte aus der Pilotphase sowie die Inkind-Leistungen innerhalb der Projekte.

OeAD, Horizon Europe) and EU programmes with regional co-financing (LE 14–20, etc.) (see Tab. 1 and Fig. 2). A substantial – although not explicitly quantified – contribution is provided by the in-kind efforts of project partners, who contribute significant in-kind resources both to the establishment of methods and to the generation of DNA barcodes. The *ABOL Coordination* is often involved in projects as a partner but also independently acquires third-party funding.

The costs of the *ABOL Coordination* across all phases (Fig. 2, blue) are low (6%) compared to the total funding volumes of ABOL projects that were acquired with the support of the coordination unit (Fig. 2, dark red), as well as compared to international projects in whose development ABOL was involved or which were supported by the coordination unit (Fig. 2, light red).

Developing reference data for Austrian biodiversity

Although the generation of reference data was no longer the exclusive common goal, since the majority of the funding acquired by ABOL could be obtained for applied DNA barcoding projects, it remained one of the central pillars of the initiative.

In the long-term, DNA barcodes of all Austrian organisms shall be publicly available via the international data platform BOLD. All references generated during the various phases of ABOL thus are made publicly available, except when still under processing by the authors

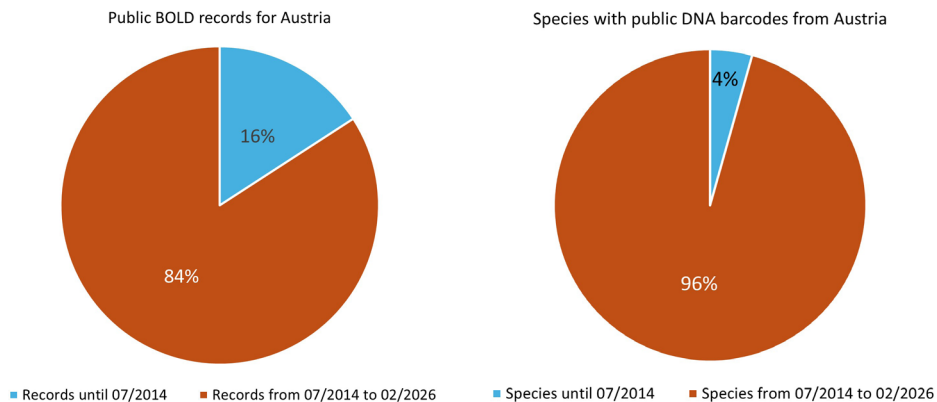


Fig. 3: Pie chart of published BOLD records for Austria. Only 16% (07/2014: 10,181 records) of currently published records (02/2026: 64,301 records) were present before the start of the ABOL pilot phase. | **Abb. 3:** Tortendiagramm der veröffentlichten BOLD-Datensätze für Österreich. Nur 16 % (07/2014: 10.181 Datensätze) der aktuell veröffentlichten Datensätze (02/2026: 64.301 Datensätze) waren vor Beginn der ABOL-Pilotphase vorhanden.

Fig. 4: Pie chart of species with DNA barcodes published in BOLD for Austria. Only 4% (07/2014: 505 species) of the currently covered species (02/2026: 11,589 species) were present before the start of the ABOL pilot phase. | **Abb. 4:** Tortendiagramm der in BOLD für Österreich veröffentlichten Arten mit DNA-Barcodes. Nur 4 % (07/2014: 505 Arten) der aktuell erfassten Arten (02/2026: 11.589 Arten) waren vor Beginn der ABOL-Pilotphase vorhanden.

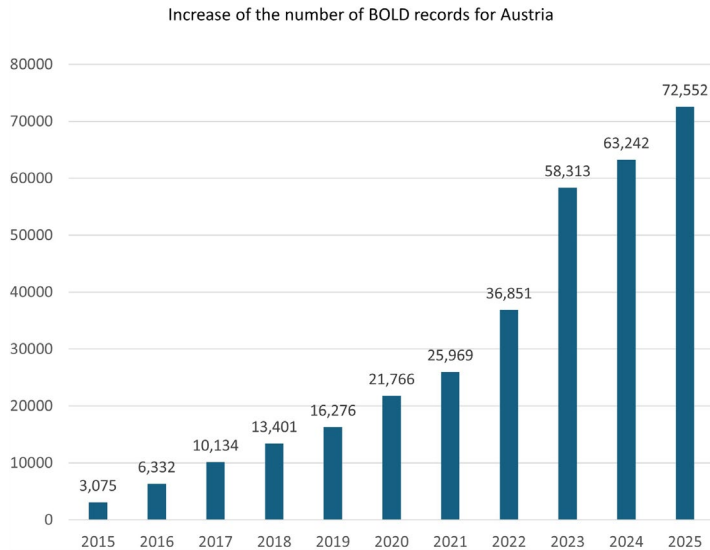


Fig. 5: Annual total numbers of records with sequences from Austrian organisms in BOLD during the period 2015 to 2025 (public and unpublished; only records included with a minimum sequence length of 300 base pairs) (data provided by the BOLD administrative team). | **Abb. 5:** Jährliche Gesamtzahl der Datensätze mit Sequenzen österreichischer Organismen in BOLD im Zeitraum von 2015 bis 2025 (öffentlich und unveröffentlicht; nur Datensätze mit einer Mindestsequenzlänge von 300 Basenpaaren wurden berücksichtigt) (Daten bereitgestellt vom BOLD-Team).

who generated the data. The *ABOL coordination* always supports partners making DNA barcodes public. With March 10, 2026, 64.301 records from Austrian organisms were publicly available in BOLD (Fig. 3). 84% of the latter were generated during the various phases of the *ABOL Coordination*.

Regarding species numbers, 96% of species with publicly available DNA barcodes in BOLD were added to the reference database during the various phases of ABOL (Fig. 4).

Overall, 70,000 records with sequences were generated and submitted to BOLD over the course of the ABOL project (Fig. 5).

Adapting the goals of ABOL

Austria's funding landscape offers limited opportunities for projects focusing on the generation of reference data, but it does provide funding schemes for applied aspects of DNA barcoding. This limitation was a major reason for the expansion of the objectives of the ABOL initiative. Initially, there was a strong focus on completion, curation and validation of the reference database and on building and maintaining a network of partners. Over the course of the main phase of ABOL, the objectives were increasingly expanded to include the promotion of biodiversity research in general (with a particular emphasis on DNA barcoding approaches). This went hand in hand with a stronger emphasis on applied aspects of DNA barcoding, the expansion of the network to include stakeholders, and on bridging science,

society, and policy. These developments were further reinforced by the growing societal relevance of biodiversity research in the face of global challenges.

ABOL-RefDat, a project funded by the Biodiversitätsfonds (BMK) and running from January 1, 2024, to October 31, 2025, is one of the first ABOL projects dedicated exclusively to the generation of DNA barcodes. This allows for a thought experiment to assess whether the initial plan to achieve DNA barcodes of 80% of all animals, plant and fungi of Austria within a ten-year period was realistic. Within the project, 5,724 DNA barcodes were generated for 2,773 species from Austria. If the total of national funding acquired by ABOL (given in Fig. 2) would have been used to generate DNA barcodes, the goal of recording 80% of Austrians biodiversity could have already been achieved. This highlights the importance of continuous funding to ensure smooth and effective progress in building a complete reference library.

The advantage of the current priorities and objectives of the ABOL initiative is the integration of data and knowledge in the multidimensional space of the biodiversity research landscape. This integration is a core task of the *ABOL Coordination*.

The significance of a coordinated ABOL initiative in the multidimensional biodiversity research space and the tasks of the *ABOL Coordination*

In the following, the significance of a coordinated ABOL initiative is described along two interdependent axes: one axis ranging from scientific infrastructures through basic research and applied research to societal relevance, and a geographical axis ranging from regional to national and international aspects. While the implementation of individual projects is a shared responsibility of all partners of the ABOL initiative, the integration of the DNA barcoding approach along these axes is among the central tasks of the *ABOL Coordination*.

Some of these tasks, such as ensuring the efficient generation of DNA barcodes, were embedded in the concept of the ABOL initiative from the outset, whereas others evolved in response to the initiative's history and to changing framework conditions. This applies in particular to the acquisition of projects through various funding schemes. Data generation within many larger and smaller independently funded projects not only poses greater challenges for coordination and harmonization (compared to a single comprehensive funding scheme as originally planned) but also led to a shift toward applied projects (Fig. 2).

Transdisciplinary dimension and societal integration: from data infrastructure through basic research to applied research and societal relevance

The ABOL initiative encompasses all aspects be they infrastructural, scientific, or societal.

To coordinate this breadth, the *ABOL Coordination* itself is structured into three strongly interconnected areas. The **e-Infrastructure management** is responsible for tasks related to data infrastructure aspects. It ensures compliance with quality standards and coordinates data flows from sub-projects to the ABOL database and from there to BOLD, as well as metadata flows to other Austrian and international biodiversity platforms. The **overall**

taxonomic coordination serves as the interface to taxonomic experts and is responsible for all matters related to the generation of DNA barcodes. It prevents undesirable duplication of efforts and helps to close gaps. By integrating molecular genetic approaches into taxonomic research, it acts as an indispensable interface between data-producing partners and scientific collections. The overall taxonomic coordination requires strong national networking and high communication skills. It coordinates information flows both among taxonomic experts and from ABOL to the public. The **ABOL management** is responsible for the applied aspects of DNA barcoding and their societal relevance. It coordinates the communication between regional, national, European and international initiatives and networks (iBOL, iBOL Europe, DiSSCo, eLTER, EOSC, etc.) and represents ABOL externally (stakeholders, media). The ABOL management provides ABOL partners with a common voice and coordinates information flows between partner institutions, between ABOL and international partners, and toward stakeholders.

As the DNA barcoding approach is generally dependent on a reference database that serves as the basis for DNA-based identification, it inherently has a strong research data infrastructure component. In the original development plan of the ABOL initiative, drafted during the pilot phase, the data infrastructure aspect – with the primary goal of building the reference database – was strongly emphasized. Due to the ultimately implemented funding model, consisting of core funding only for the *ABOL Coordination* and the acquisition of third-party funding for data and application projects, the shared objectives of the initiative expanded towards more applied aspects. This development was reinforced by the biodiversity crisis coming more into the geopolitical focus. The ABOL long-term objectives thus also include the general promotion of biodiversity research and monitoring, as well as support for the transformation toward a nature-positive society.

As a result, the objectives of the ABOL initiative now span the full dimension from data infrastructure through basic research and applied research to societal relevance.

Infrastructure aspects of ABOL

One of the main objectives of the ABOL initiative is to achieve a high coverage of DNA barcodes for organisms occurring in Austria, thus contributing to the international initiative iBOL and its data portal BOLD. By the end of 2025, DNA barcodes for approximately one third of the roughly 75,000 animal, plant, and fungal species occurring in Austria were available in BOLD – note that during the course of ABOL the estimated number of species increased from originally 70.000 to 75.000, based on new publications (Geiser 2018; Schratt-Ehrendorfer et al. 2022; Krisai-Greilhuber 2015). However, part of the data in BOLD is not yet publicly accessible, for example because it is still under embargo pending publication. The *ABOL Coordination* continuously strives to increase the proportion of publicly accessible data and provides partners with support in data management.

DNA barcoding is a collection-oriented scientific approach. DNA barcodes from reliably identified organisms serve as reference sequences for species identification. Voucher specimens of these reference organisms are deposited in scientific collections, ensuring the traceability of the identifications and their anchoring in physical objects. The digital storage of metadata of reference organisms, ideally complemented by digitized specimens, creates

an interface with the national scientific data infrastructure project OSCA (Open Scientific Collections Austria, <https://osca.science/en/>; Korth et al. 2025).

The *ABOL Coordination* is committed to the highest quality standards and ensures that data of the highest possible quality are made available for research and application. Accordingly, the ABOL mission statement formulates the following quality standards: DNA barcoding sequences are generated from taxonomically (a priori) identified organisms. Reference organisms originate either from publicly accessible scientific collections or, if freshly collected, are deposited in such collections. Where available, remaining DNA is stored in a DNA/tissue bank. DNA barcodes are uploaded together with the associated metadata (i.e. data that describes characteristics of other data – e.g. the name of the person which performed the morphological species identification) to the international database BOLD. All steps in the DNA barcoding workflow – from collection and documentation through sampling, DNA analysis, data evaluation, and data submission – are carried out in strict compliance with the highest (laboratory) standards and controls. All data, whether DNA barcodes or application data, are made publicly available whenever possible in accordance with the FAIR principles.

The *ABOL Coordination* regularly offers workshops for partners and other interested parties, like e.g. participants of the ABOL BioBlitzes and managers of protected areas, on the use of *Specify* (ABOL database) and BOLD as well as on topics related to data collection, quality assurance, and biodiversity informatics. These activities contribute to broad knowledge transfer within the community and strengthen capacity building in modern biodiversity research. Between 2017 and 2025 in total 18 workshops have taken place with more than 150 participants.

The ABOL website also provides a platform for showcasing the diverse projects of the ABOL initiative and thus supports the dissemination obligations of many partners. Through this visibility and active communication, the website functions as a central element of multi-dimensional integration into the larger context – from national monitoring programs and international research infrastructures to global biodiversity strategies.

The Austrian research funding landscape offers limited opportunities for submitting purely data infrastructure projects. Likewise, European funding programs for research infrastructures mostly do not allow for data generation. Nevertheless, several projects with a predominantly infrastructural character have been implemented. Through these activities, the ABOL initiative has contributed at a technical level to the establishment and expansion of IT infrastructure and laboratory capacities at several universities. For example, between 2017 and 2021, a major infrastructure project for establishing DNA barcoding pipelines at universities was carried out under the HRSM project (Hochschulraumstrukturmittel; <https://www.abol.ac.at/en/project/hrsm-project/>), funded with EUR 1 million by the Ministry of Science. This collaborative project involved the *ABOL Coordination* (NHMW) and five Austrian universities (lead: University of Graz).

By generating DNA barcodes connected to new voucher specimens, ABOL has also contributed to the expansion of scientific collections at partner museums. In the project **ABOL-RefDat**, funded by the Biodiversity Fund (BMK, later BMLUK), 5,724 novel DNA barcodes were generated for 5,509 individuals (of 2,773 Austrian species) (<https://www.abol.ac.at/en/project/abol-refdat-2/>). The project was acquired and coordinated by the *ABOL*

Coordination. In addition to data production, a key objective was the involvement of various institutions and experts.

However, the reference data in BOLD do not represent the only data infrastructure component of ABOL. ABOL also aims to make all data generated through DNA barcoding applications in Austria available for reuse. With the involvement of a university-based ABOL consortium, the project **ATIV-Biodat** (<https://www.abol.ac.at/en/project/ativ-biodat-2/>) is currently underway, aiming to establish a trans-university infrastructure for linking national and international biodiversity databases.

Aspects of basic research

Promoting taxonomic research in Austria is among the main objectives of the ABOL initiative. A central task of the *ABOL Coordination* is the integration of DNA-based methods into taxonomy. This integrative taxonomic approach, which combines taxonomic classification based on phenotypic (i.e. morphological or behavioral traits) and genotypic (i.e. DNA barcodes) characteristics, increases the direct relevance of taxonomic research for applied biodiversity research, making ABOL an important hub for biodiversity research and documentation in Austria (e.g. Kirichenko et al. 2015; Reier et al. 2019; Schäffer et al. 2019 a, b). The long-term goal of the ABOL initiative is a complete inventory of all animal, plant, and fungal species in Austria. The *ABOL Coordination's* task is to make the generation of the required DNA barcodes as efficient as possible and to minimize duplication among partner institutions. This agenda aligns closely with the research focus of museums and scientific collections in general. By generating DNA barcodes, important information connected to physical reference organisms is made accessible to society; accordingly, the establishment of the reference database also falls within the scope of digitization initiatives of scientific collections that follow the extended specimen concept (Webster 2017).

DNA barcoding has great potential for detecting cryptic diversity (e.g. Huemer et al. 2014b; Eschner et al. 2015; Schäffer et al. 2019a, b; Reier et al. 2020b). One highlight was the discovery of a fish species previously unknown from Austria in the upper Mur River. The emerald gudgeon (*Romanogobio skywalkeri*) was newly described (Friedrich et al. 2018), and its distribution and population structure are currently being investigated in a dedicated project (<https://www.abol.ac.at/project/smaragdgressling-2/>).

Genetic data form the basis for numerous scientific studies, for example in taxonomy, phylogenetics, population genetics, or ecology. Thus, they constitute perfect showcases for reuse of collection data.

Aspects of applied research

The DNA barcodes in the reference database form the basis for numerous applications. Once established and intercalibrated with traditional approaches, DNA barcoding offers a cost- and time-efficient complementary method for species identification of animals, plants, and fungi in many fields. Thus, the *ABOL Coordination* integrates not only taxonomic research with molecular genetic research, but also with systematic and conservation-relevant research.

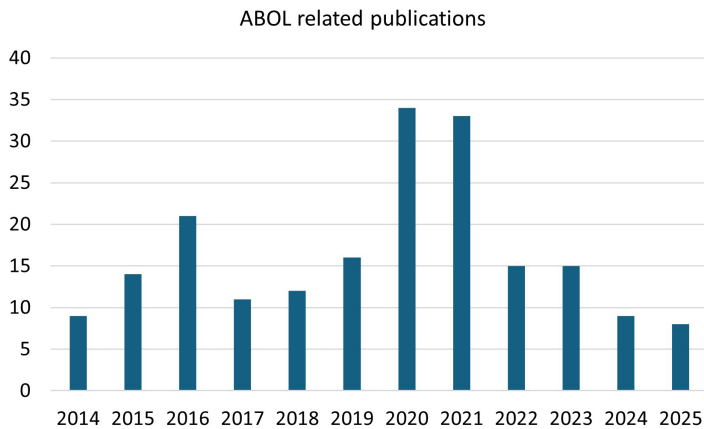


Fig. 6: Number of scientific publications in the context of ABOL per year. | **Abb. 6:** Anzahl der Veröffentlichungen im Kontext von ABOL pro Jahr.

In addition to high-quality reference data, the establishment and application of DNA barcoding approaches – particularly in the analysis of mixed samples (metabarcoding) and environmental samples (eDNA metabarcoding) – serve to establish DNA barcoding as a complementary species identification approach.

Like other initiatives at the European and global level, ABOL promotes the establishment of genetic methods in biodiversity monitoring and applied research. This includes projects on the use of DNA barcoding to detect pathogens causing swimmer's itch in water bodies (Reier et al. 2020a; Helmer et al. 2021, 2023), as well as the identification of dragonflies using DNA from exuviae (Sittenthaler et al. 2023a, b).

The **BioPlanbar** project aimed to integrate DNA barcoding and metabarcoding into the preparation of environmental impact assessments (Kobl Müller et al. 2019).

Thanks to close cooperation between the *ABOL Coordination* and stakeholders, applications are continuously adapted to stakeholder needs. In the **GeMonA+** project, a genetic module is being developed in cooperation with LTER-Austria as a contribution to a holistically coordinated biodiversity monitoring system in Austria.

The scientific achievements of ABOL in both basic and applied research are most clearly reflected in the number of scientific publications generated during the various phases of the ABOL initiative (Fig. 6).

Aspects of outreach and societal value

Outreach into society is one of the defining strengths of ABOL. It distinguishes the initiative from many purely scientific projects and helps to foster a culture of shared responsibility for biodiversity.

The *ABOL Coordination* acts as a central interface – a unifying element that holds together the multidimensional construct of the ABOL initiative – and makes it visible through public outreach activities (lectures, workshops, newsletters, social media activities, and its own website). The goal is to present complex topics such as genetic species identification in an accessible way and to highlight their benefits for society, conservation, and policy. This strengthens the acceptance of molecular genetic methods within the biodiversity discourse and integrates scientific knowledge into society. Since 2020, ABOL has jointly organized conferences with the Biodiversity Hub; these were held as multi-day biodiversity conferences in 2023 and 2025 under the title *Days of Biodiversity*, together with other organizers. These events featured a highly diverse program that brought together players from biodiversity research and practice, decision-makers from politics and administration, NGOs, interested citizens, and the media.

In addition, the **ABOL BioBlitzes** (Sonnleitner et al. 2022) promote the participation of community scientists in the generation of scientific knowledge. Initiated by the *ABOL Coordination* in 2019, altogether 37 BioBlitzes have been performed (Tab. 2). They involve

Tab 2: Overview of the ABOL BioBlitzes between 2019 and 2025. | **Tab. 2:** Überblick über die ABOL-BioBlitze zwischen 2019 und 2025.

ABOL-BioBlitz	Year	Location
Test BioBlitz (“Probeblitz”)	2019	Tattendorf, Lower Austria
GEO Day of Nature, Biosphere Reserve Nockberge	2019	Diversity in shores and slopes at Millstätter See, Carinthia
Day of Biodiversity Upper Austria	2019	Grein – around Mühlberghof, Upper Austria
Day of Biodiversity, Biosphere Reserve Wienerwald	2019	Pressbaum, Lower Austria
Day of Biodiversity Vienna	2019	BOKU university area, Knödelhüttenstraße, 1140 Vienna
Day of Biodiversity Tyrol	2019	Brandenberg valley, municipality Brandenburg, Tyrol
Day of Biodiversity National Park Hohe Tauern	2019	Gössnitz valley, Carinthia
Day of Biodiversity, Biosphere Reserve Wienerwald	2020	Pötzleinsdorfer Schlosspark, Geymüllergasse, 1180 Vienna
GEO Day of Nature, Biosphere Reserve Nockberge	2020	Around Grundlalm, Carinthia
Day of Biodiversity National Park Hohe Tauern	2020	Umbal valley, East Tyrol
Day of Biodiversity Tyrol	2020	Municipality Gössen, Tyrol
Day of Biodiversity Vienna	2021	Donauinsel, 1220 Vienna
Day of Biodiversity, Biosphere Reserve Wienerwald	2021	Eichgraben, Lower Austria

ABOL-BioBlitz	Year	Location
GEO Day of Nature, Biosphere Reserve Nockberge	2021	Zunderwand near Kaning, Radenthein, Carinthia
Day of Biodiversity Tyrol	2021	Municipality Pfunds, Tiroler Oberland, Tyrol
Day of Biodiversity National Park Hohe Tauern	2021	Municipality Muhr in the Lungau, Salzburg
Day of Biodiversity, Biosphere Reserve Wienerwald	2022	Ottakring, 1160 Vienna
Insect Camp	2022	Leiser Mountains, Lower Austria
Day of Biodiversity Tyrol	2022	Ehrwalder Becken, Tyrol
GEO Day of Nature, Biosphere Reserve Nockberge	2022	St. Lorenzen ob Reichenau, Carinthia
Day of Biodiversity National Park Hohe Tauern	2022	Malta valley, Carinthia
Day of Biodiversity Vienna	2023	Garden plot – ÖBB Landwirtschaft BBL – Region Ost Zweigverein Kagan, 1210 Vienna
Day of Biodiversity, Biosphere Reserve Wienerwald	2023	Klosterneuburg, Lower Austria
Insect Camp	2023	Nature Park Weißbach near Lofer, Salzburg
GEO Day of Nature, Biosphere Reserve Nockberge	2023	between Peitlernock and Bärenauock in Innerkrams, Carinthia
Day of Biodiversity Tyrol	2023	Leutasch, Tyrol
Day of Biodiversity National Park Hohe Tauern	2023	Defreggen valley, East Tyrol
Day of Biodiversity, Biosphere Reserve Wienerwald	2024	Liesing, 1230 Vienna
GEO Day Carinthia	2024	Geo park Karawanken, Carinthia
GEO Day of Nature, Biosphere Reserve Nockberge	2024	around lake Windebensee (at the Nockalm road), Carinthia
Insect Camp	2024	Nature Park Karwendel, Tyrol
Day of Biodiversity National Park Hohe Tauern	2024	Habachtal, Salzburg
Day of Biodiversity Vienna	2025	Area Breitenlee, 1220 Vienna
Day of Biodiversity, Biosphere Reserve Wienerwald	2025	Baden near Vienna, Lower Austria
Insect Camp	2025	Nature Park Hohe Wand, Lower Austria
Day of Biodiversity National Park Hohe Tauern	2025	Gradental (Schobergruppe) in the National Park municipality Großkirchheim, Carinthia
GEO Day Carinthia	2025	Mittagskogel, Karawanken, Carinthia

community scientists with high biodiversity expertise collecting samples that contribute to building the reference database. Beyond integrating new partners into the ABOL initiative, the ABOL BioBlitzes also serve science communication, public outreach, and early-career support by enabling the validation of morphological identifications through DNA barcoding. In workshops offered by the *ABOL Coordination*, taxonomic experts can learn how to process their DNA barcoding data and thus contribute to the curation of the DNA reference database. The ABOL BioBlitzes are also listed on the national citizen science platform “Österreich forscht.”

The *ABOL Coordination* communicates the goals of the initiative to policymakers. It maintains contacts with stakeholders such as ministries, authorities, and the Environment Agency Austria (Umweltbundesamt), and is engaged in committees and organizations. Members of the *ABOL Coordination* (Nikolaus Szucsich and Elisabeth Haring) represent the *ABOL Coordination* on various scientific advisory boards and bodies, such as the Austrian Biodiversity Council and the Austrian Academy of Sciences’ Commission for Biodiversity in Austria (“Biodiversity Austria, Biodiv-A”), where they are also involved in IPBES-related matters. The biodiversity community, which was already brought together during the ABOL pilot phase, formed the basis for the establishment of the Austrian Biodiversity Council (<https://www.biodiversityaustria.at/biodiversitaetsrat/>), which was thus able to build on an existing network.

The transdisciplinary character of the ABOL initiative is also reflected in the ABOL network itself. From the outset of the ABOL pilot phase, numerous institutions and individuals expressed interest in participating in ABOL. This partner network grew substantially over subsequent phases and now includes staff from many institutions – including all Austrian universities active in biological research, federal and regional museums, biosphere reserves, national parks, nature conservation departments, NGOs – as well as numerous individuals (<https://www.abol.ac.at/en/about-us/#cooperation-partners>).

Within the network, partners assume very different roles and functions. Only some are involved in generating DNA barcodes, usually within the framework of third-party funded projects. Others contribute to methodological development, applied projects, or act as stakeholders (e.g. representatives of protected areas) who are integrated into projects. The *ABOL Coordination* has organized workshops to convey DNA barcoding expertise and knowledge of the BOLD reference database to stakeholders. The ABOL conferences organized by the *ABOL Coordination* (from 2020 onward replaced by ABOL’s participation in the *Days of Biodiversity*) also served as platforms for the exchange of knowledge and experience.

Particularly noteworthy is the establishment of a successful consortium consisting of the *ABOL Coordination* and university staff from several Austrian universities. This consortium has already completed a major infrastructure project for establishing DNA barcoding pipelines at universities (HRSM project) and is currently conducting further projects (notably GeMonA+ and ATIV-Biodat).

Geographical dimension: from regional and national to European and global aspects

The ABOL initiative is closely linked to European and international biodiversity research infrastructures. A central element of this networking is the systematic integration of DNA barcodes generated in Austria into the international data portal BOLD.

The *ABOL Coordination* is closely connected to European and international biodiversity research infrastructures. International networking is indispensable to ensure the comparability of biodiversity indices when addressing global challenges. ABOL coordinator Nikolaus Szucsich has been a member of the iBOL Science Committee since 2015 (<https://ibol.org/about/science-committee/>) and represents the ABOL initiative within the European subsidiary organization iBOL Europe.

Via OSCA (Open Scientific Collections Austria) (Korth et al. 2025), ABOL is linked to DiSSCo (Distributed System of Scientific Collections), a European initiative that promotes the digitization and networking of scientific collections at the European level.

Knowledge transfer also takes place across national borders, for example within the framework of an OeAD project in Zambia, in which two DNA barcoding workshops were held for staff and students at the University of Zambia in Lusaka (lead: University of Graz; <https://www.abol.ac.at/project/sambia/>).

The global Horizon Europe project LIFEPLAN (<https://www.helsinki.fi/en/projects/lifeplan>) is an iBOL project that investigates the impact of human land use (especially settlement) on biodiversity. At more than 200 twin sites – each comprising a pair of one near-natural and one urban location – biodiversity is surveyed using Malaise traps, spore traps, soil samples, camera traps, and microphones. ABOL partners are involved with three twin sites in LIFEPLAN. The use of state-of-the-art approaches (ranging from metabarcoding to artificial intelligence; Hardwick et al. 2023) and analytical methods will contribute to advancing our understanding of global biodiversity.

The *ABOL Coordination* likewise represented ABOL in the EU COST Action DNAqua-Net (Leese et al. 2016). The aim of this EU COST Action was to establish an interdisciplinary research network focusing on the development of gold standards for novel biodiversity-relevant indices using DNA-based approaches for the ecological assessment of European waters (Elbrecht et al. 2017; Pawlowski et al. 2021; Blancher et al. 2022). In addition to a gap analysis (Weigand et al. 2019) and the development of standardized approaches (Meissner et al. 2021), DNAqua-Net provided a learning platform for the next generation of European researchers, preparing them for new technologies. Together with water management authorities, policymakers, and other stakeholders, the group developed a concept for the routine application of DNA-based tools within legally binding assessment frameworks.

The *ABOL Coordination* team

Since the start of the project, an interdisciplinary team has been built up that covers the three areas of the *ABOL Coordination* (see also 3.1.). The *ABOL Coordination* currently consists

of the following team members (in total 2.5 FTE): Nikolaus Szucsich has the leading role as the ABOL Manager; Michaela Sonnleitner, Janine Heinzl and Victoria Kargl are responsible for overall taxonomic coordination and act as ABOL BioBlitz coordinators. Florian Ackerl works as e-infrastructure manager. Former members encompass Denise Grau and Oliver Macek (as former e-infrastructure managers) and Christoph Leeb and Sabine Schoder (in taxonomic coordination).

Institutional embedding: The anchoring of the *ABOL Coordination* at the Natural History Museum Vienna is based on the fact that DNA barcoding is inherently a collection-based approach to DNA-based species identification. The aim is to consistently maintain the link between the DNA barcode and the collection object (reference individual). This traceability enables transparency and quality control. Currently Elisabeth Haring and Christoph Hörweg are the project leaders of the *ABOL Coordination*. Former project leaders encompass Helmut Sattmann and Christian Bräuchler.

The *ABOL Coordination* is supported and accompanied by the Scientific Advisory Board established in 2017. The composition and development of the coordination team and the Scientific Advisory Board are available on the ABOL website (<https://www.abol.ac.at/en/about-us/>).

Challenges, outlook, and vision

The network as key asset

By integrating various individuals and institutions, as well as different research fields and stakeholders, the *ABOL Coordination* ensures the creation of synergies, the pooling of resources, and continuous knowledge transfer between science, society, administration, and political decision-makers. Over the past decade, the ABOL initiative has evolved from a funded project into a central platform for biodiversity research in Austria. Its network function is not a “by-product” but rather the backbone of the initiative, initiated and continuously developed by the *ABOL Coordination*.

United by the common goal of promoting biodiversity research, the coordinated ABOL initiative brings together universities, research institutions, museums, and other collections. This allows expertise from classical taxonomy, molecular biology, bioinformatics, and applied ecology to be combined. Without this platform, many collaborations would not have come about, and one of the future tasks of ABOL will therefore be to continuously strengthen and promote these connections. The benefits of the ABOL network are evident in numerous project-level collaborations – both small and large – often spanning institutions and disciplines and/or involving community scientists, thereby facilitating substantial knowledge exchange and transfer.

The ABOL network also has an outward impact: through participation in European projects e.g. DNAqua-Net (Leese et al. 2016) or TETTRIs (Magee 2025), and data flows into international platforms (BOLD, GBIF). ABOL is embedded in global biodiversity initiatives. This enhances the international visibility of Austrian biodiversity initiatives and strengthens their integration into global networks and international forums. ABOL also

fulfils a networking function through its involvement in advisory bodies (e.g. the Austrian Biodiversity Council; the Austrian Academy of Sciences' Commission for Biodiversity in Austria – “Biodiversity Austria (Biodiv-A)”) and through its links with various relevant national platforms (e.g. the Austrian Biodiversity Atlas, GBIF Austria, ZOBODAT).

Over more than a decade, the *ABOL Coordination* has evolved as a servant of many masters: regarding involved institutions, it covered scopes from basic research to various applications of species identification, geographical perspectives from regional to global scales, and connected with stakeholders, politics, and society.

To maintain these bridging functions, it would be most appropriate to strive for a jointly financed consolidation. Associating the *ABOL Coordination* with a single institution would risk restricting its activities to institutional agendas. One way to mitigate such risks would be to integrate the *ABOL Coordination* into a national biodiversity centre, as proposed by the Biodiversity Council of Austria.

The maintenance of such a network is time-consuming and resource-intensive and requires secure coordination to ensure continuous communication, alignment, and strategic development. This coordination work enables the networking of experts across institutions, disciplines, and regions, thereby creating the framework for cooperative research and the shared use of resources.

The *ABOL Coordination* as a long-term infrastructure

The *ABOL Coordination* provides its partners with comprehensive support in data processing and quality control and assists with data preparation for international platforms such as BOLD. Continuing this way in the future, the *ABOL Coordination* delivers central services that are in high demand within the community and clearly position the initiative as a national research infrastructure. Running a working database based on *Specify* (Mengarelli et al. 2025) enables a linkage of taxonomy, DNA sequences, metadata, and scientific collections, creating an integrated data environment that functions both as an internal tool for the *ABOL Coordination* and as an interface for partners preparing data for upload to BOLD. Thus, the *ABOL Coordination* can maintain its role in quality assurance by giving structured feedback to taxonomic experts, thus fostering the continuous improvement of the reference data.

Yet, while some of the services provided by the *ABOL Coordination* are readily measurable, reducing its role to a purely infrastructural function would neither adequately reflect the scope of its activities nor meet the needs of the community. One of the major roles of the *ABOL Coordination* is the internal and external communication of the ABOL initiative.

Driving innovation in biodiversity research through ABOL

Since its establishment, ABOL has significantly advanced biodiversity research in Austria by combining coordinated research activities with strong efforts in mobilization, networking, and community building. Research projects have been central to this development, providing both scientific outputs and the framework for collaboration among museums, universities, regional initiatives, and taxonomic societies. For the further development of

DNA-based biodiversity research in Austria, continuing and expanding these collaborative structures will remain essential.

From a scientific perspective, several areas will require particular attention. A major challenge remains the identification and documentation of cryptic diversity, which continues to reveal previously overlooked species and evolutionary lineages and the hidden diversity, especially in megadiverse groups of organisms. In addition, further standardization of laboratory protocols, data generation, and reference libraries will be crucial to ensure comparability and long-term usability of DNA barcode data. Finally, the application of DNA-based methods in biodiversity monitoring is rapidly gaining importance. Strengthening the integration of DNA barcoding and metabarcoding approaches into ecological monitoring and conservation practice will be a key task for the coming years.

Through its coordinated network and reference data generation, ABOL provides an essential foundation for these developments and will continue to play a central role in advancing biodiversity research and evidence-based conservation in Austria.

The future of ABOL along the dimension from data infrastructure to societal outreach

The global biodiversity crisis represents a major societal challenge that requires coordinated scientific responses. This challenge must be addressed not only at the international level but also within Austria. Effectively tackling biodiversity loss requires a coordinated research agenda, in which multiple institutions and disciplines collaborate toward shared objectives.

Given the complexity of biodiversity research – spanning taxonomy, ecology, molecular biology, environmental monitoring, data management, and policy-relevant applications – coordination is essential to ensure coherence, avoid duplication of efforts, and maximise the societal impact of research activities. A coordinated framework can facilitate the integration of expertise across institutions and promote the development of shared infrastructures and standards.

With more than a decade of experience in connecting research institutions, infrastructures, and application-oriented stakeholders, the *ABOL Coordination* is well positioned to assume a central role in such a framework. It contributes to addressing societal challenges on several interconnected levels, i.e. the data infrastructural level, the level of research, as well as the level of networks, by linking biodiversity research with societal and political decision-making.

Overcoming the societal challenges needs a strong base in data infrastructures, committed to the FAIR data principles. By ensuring a close linkage between data, databases, and scientific collections, the *ABOL Coordination* will continue to contribute to a dynamic global data infrastructure network. At the same time, it itself functions as an infrastructure.

Intensified and increased efforts of biodiversity research are necessary to allow for evidence-based solutions. Thanks to the *ABOL Coordination* the initiative has successfully established itself as a key structure within Austrian biodiversity research. Future progress will need a balanced combination of research infrastructure development connecting scientific collections as well as national and international platforms and data networks, to achieve

long-term frameworks for data generation, storage, and accessibility. Ideally this is implemented through partnerships among key institutions such as the Universities, the Natural History Museums, regional biodiversity hubs, and the numerous scientific societies and associations that often harbor rare biodiversity expertise. At the same time, scientific progress will rely on extended research funding (e.g. FWF, EU programs) specifically dedicated to establishing the data infrastructure needed.

More than ever, overcoming scientific challenges demands for effective collaboration through well-functioning networks of scientists, nature conservation practitioners, authorities and policymakers, to finally foster a broader societal transformation toward a more sustainable and nature-compatible society. Here, the network of ABOL partners is a strong pillar for Austria, well integrated into the international context.

Crucial to the future viability of the initiative is the establishment of a permanently secured, professionally operating, and strategically embedded coordination structure. Only under these conditions can ABOL further expand its role as a national platform for biodiversity research, provide stable infrastructure for data, expertise, and knowledge transfer, and make substantial contributions to the implementation of national and international commitments in the fields of nature conservation and biodiversity monitoring. At a time when framework conditions are changing at all levels and demands on biodiversity research continue to grow, an initiative can only be successful in the long term if coordination functions are performed reliably and continuously.

ABOL stands at a decisive point in its development, facing the challenge of securing its activities over the long term while strategically expanding its scope to a broader initiative that supports biodiversity research in general. In particular, this necessitates sustainable funding of the central coordination unit and the integration of its activities into national and international biodiversity monitoring programs (Basille et al. 2024). With the *ABOL Coordination* forming the organizational backbone of ABOL, the initiative can remain functional as a decentralized network.

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Crustacean stygofauna in the urban shallow aquifers of Vienna, Austria – biodiversity, community dynamics and environmental drivers

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This study investigates the diversity and ecological patterns of stygobiont and stygophile crustaceans in shallow groundwater of the city of Vienna, Austria, with a particular focus on amphipods. In total, 47 crustacean taxa were identified, revealing an unexpectedly high diversity in this urban setting. Among these, seven amphipod species were confirmed, largely matching known biogeographic distribution patterns. Molecular analyses based on COI gene sequencing refined amphipod species identification based on morphology and revealed the presence of a potentially undescribed taxon (*Niphargus* aff. *aquilex*) as well as the most eastern record of *Niphargus tonywhitteni*. Availability of dissolved oxygen and associated redox conditions, as well as microbiological-ecological indicators were key in explaining the spatial distribution of taxa. Groundwater temperature and hydrogeology (aquifer type) further influenced occurrence patterns, particularly with respect to amphipods, which preferred lower temperatures and larger sediment pore space. In addition, community-level analyses identified the influence of surface waters as a significant determinant of community composition. Seasonal effects were almost absent. The high overall community homogeneity as well as the limited species-specific environmental preferences among amphipods provide evidence that basic conservation measures are likely to benefit multiple taxa concurrently. However, rare species warrant further targeted investigations. Overall, this study highlights the ecological value of urban aquifers.

Nilles C, Englisch C, Zittra C, Scharhauser F, Fuchs A, Gaviria S, Kaminsky E, Stumpp C, Steiner C, Buga-Nyéki E, Karwautz C, Griebler C (2026) Crustaceen Stygofauna in den urbanen, oberflächennahen Grundwasserleitern von Wien, Österreich – Biodiversität, Gemeinschaftsdynamiken und umweltbedingte Einflussfaktoren

Diese Studie untersucht die Diversität und die ökologischen Muster stygobionter und stygophiler Krebstiere im oberflächennahen Grundwasser der Stadt Wien, Österreich, mit besonderem Fokus auf Amphipoden. Insgesamt wurden 47 Krebstiertaxa identifiziert, was eine unerwartet hohe Diversität für diesen urbanen Lebensraum offenbart. Darunter konnten sieben Amphipodenarten nachgewiesen werden, deren Vorkommen weitgehend den bekannten biogeographischen Verbreitungsmustern entspricht. Molekulargenetische Analysen auf Grundlage des COI-Gens präzisierten die auf morphologischen Merkmalen basierende Artbestimmung der Amphipoden und unterstreichen das Vorkommen eines potenziell unbeschriebenen Taxons (*Niphargus* aff. *aquilex*) sowie den bislang östlichsten Nachweis von *Niphargus tonywhitteni*.

Die Verfügbarkeit von gelöstem Sauerstoff und damit verbundene Redoxbedingungen sowie mikrobiologisch-ökologische Indikatoren erwiesen sich als zentrale Faktoren zur Erklärung der räumlichen Verteilung der Fauna. Auch die Grundwassertemperatur und die Hydrogeologie (Aquifertyp) beeinflussten die Verteilungsmuster, insbesondere bei Amphipoden, die niedrigere Temperaturen und größere Porenräume im Sediment bevorzugten. Gemeinschaftsanalysen identifizierten darüber hinaus den Einfluss von Oberflächengewässern als einen signifikanten Treiber für die Zusammensetzung der Gemeinschaften. Saisonale Effekte waren weitestgehend nicht nachweisbar.

Die insgesamt hohe Homogenität der Lebensgemeinschaften sowie die begrenzten artspezifischen Umweltpreferenzen der Amphipoden legen nahe, dass grundlegende Schutzmaßnahmen wahrscheinlich vielen Taxa gleichzeitig zugutekommen würden. Seltene

Arten erfordern jedoch weiterhin gezielte weiterführende Untersuchungen. Insgesamt unterstreicht diese Studie den ökologischen Wert urbaner Grundwasser-Systeme.

Keywords: stygofauna, groundwater biodiversity, urban aquifers, COI barcoding, environmental drivers, crustacea, groundwater ecology, Amphipoda.

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Introduction

Groundwater is a globally essential resource, supplying drinking water, irrigation, and industrial uses, and represents the most extracted raw material worldwide (Wada et al. 2010; Lall et al. 2020). Beyond its societal importance, groundwater sustains aquatic and terrestrial ecosystems and constitutes the largest continental aquatic biome (Kløve et al. 2011; Griebler et al. 2023a). These ecosystems harbor largely unexplored biodiversity, including microorganisms and groundwater fauna, which perform key ecological functions such as water purification, contaminant attenuation, pathogen control, and the maintenance of subsurface connectivity through bioturbation (Griebler & Avramov 2015; Feichtmayer et al. 2017; Stumpp & Hose 2017; Hose & Stumpp 2019; Mammola et al. 2026). In this sense, ecosystem integrity is maintained by the activity of groundwater fauna, which creates and reserves open pore space essential for water flow, transport of materials and replenishment of dissolved oxygen and organic matter, thereby governing geochemical processes.

Due to restricted energy input, long water residence times, limited dispersal, and high ecological specialization, groundwater ecosystems are energy-poor and particularly vulnerable to disturbance (Hose et al. 2022). While they often host comparatively high numbers of rare, relict, and endemic species (Gibert et al. 2009; Humphreys 2009; Mammola et al. 2019, 2022; Wynne et al. 2021; Di Lorenzo et al. 2024; Englisch et al. 2024), their biodiversity remains poorly documented and is largely underrepresented in conservation and management frameworks (Sánchez-Fernández et al. 2021; Mammola et al. 2022, 2024). The limited accessibility of subsurface habitats and the scarcity of systematic surveys across

different land use types constrain our understanding of species distributions and ecological requirements.

In urban areas, like the city of Vienna, Austria, groundwater ecosystems are influenced by a multitude of anthropogenic stressors. In addition to the environmental drivers that are present in natural systems (e.g. oxygen and food availability, hydrogeological conditions like pore space, geohistorical background, hydrological exchange), groundwater fauna in urban aquifers is impacted by pressures like pollution, reduced groundwater recharge due to surface sealing, subsurface infrastructure, groundwater warming and subsurface urban heat islands, all potentially resulting in habitat loss and biodiversity decline, and in the worst case leading to a disturbance and loss of ecosystem functioning (Griebler et al. 2019; Castaño-Sánchez et al. 2020; Becher et al. 2022; Englisch et al. 2024). To date, groundwater fauna communities in urban areas have received particularly little attention, as only a few studies have been conducted in cities in Central Europe (Koch et al. 2021; Dumnicka et al. 2025a, 2025b). In Vienna specifically, only single species records of groundwater fauna existed from single wells with exception of the Lobau National Park area (Vornatscher 1938, 1972; Danielopol 1984; Pospisil 1994; Griebler et al. 2023b). Therefore, one aim of this study was to compile a comprehensive species inventory of the groundwater crustacean fauna in Vienna. The focus was on crustaceans (including Cladocera, Ostracoda, Harpacticoida, Cyclopoida, Amphipoda, Isopoda, Bathynellacea), because they generally constitute the majority of stygofauna and determination to species level can be achieved for most groups.

Invertebrate fauna in groundwater includes organisms that exclusively inhabit aquifers (stygobionts), preferentially or temporarily inhabit subsurface aquatic environments (stygophiles), or lack adaptations to the subterranean habitats and are either accidentally transported there or act as invasive colonizers from the surface (stygoxenes). Groundwater habitats are characterized by permanent darkness, which creates unique ecological niches and nutrient cycling processes that differ substantially from surface ecosystems (Thulin & Hahn 2008). Although subterranean habitats are environmentally stable, they depend largely on surface-derived organic matter, often resulting in low oxygen concentrations due to limited replenishment (Hahn 2002). Adaptations such as eye reduction, depigmentation, body elongation, low metabolic rates, extended lifespans, and reduced reproductive output reflect specialization to energy-poor and spatially constrained environments (Hahn 2002; Boulton et al. 2008; Hose et al. 2022). These adaptations are reflected in phylogenetic diversity and cryptic species. In this study, particular emphasis in combining morphological and molecular identification was placed on stygobiont amphipods to delineate species and link them to specific niches. Amphipods were chosen to first expand the knowledge on their distribution, and second, making use of recently established protocols for molecular analysis (Fišer et al. 2019; Alther et al. 2021; Borko et al. 2021).

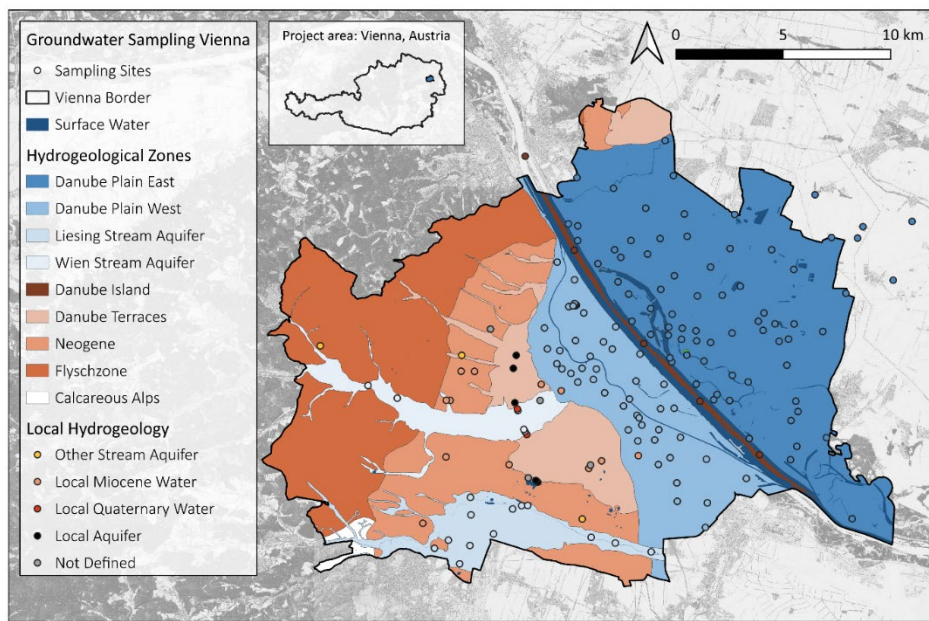
Beyond providing new insights into the crustacean biodiversity of Vienna's urban shallow groundwater, this study aims to identify environmental factors key to the distribution and community assembly of groundwater crustaceans in general and amphipods in particular. By this, we seek to expand our understanding of urban groundwater ecosystems and their associated crustacean fauna, thereby providing support for the development of sustainable groundwater management strategies and effective conservation planning.

Materials and Methods

Study area

Vienna, capital of Austria and fifth-largest city in the European Union with more than two million inhabitants, is located in the northeastern part of Austria at the Danube River. The city spans 414.87 km², with elevations from 151 m a.s.l. in the Lobau floodplain to 543 m at the Hermannskogel (MA 23 der Stadt Wien, 2024). Green areas and water bodies cover 53.1% of the city area. A total of 40,5% of the city is designated as protected, notably the Lobau wetland within the Danube Floodplain National Park and the Vienna Forest (Wienerwald) (MA 23 der Stadt Wien 2024). Land use comprises approximately 10.9% agriculture, 19.6% traffic, and 16.4% built-up areas (MA 23 der Stadt Wien 2024). Vienna's hydrogeology is highly heterogeneous (Fig 1), described in detail in Kaminsky et al. (2025a).

Vienna has a temperate climate, with 2021 averaging 11.1 °C and 583 mm of precipitation, and 2022 being warmer and drier at 12.2 °C and 461 mm (MA 23 der Stadt Wien 2024). Long-term precipitation averages around 650 mm per year (Stadt Wien 2025), but there



Data sources: Basemap Austria (<https://www.basemap.at/wmts/1.0.0/WMTSCapabilities.xml>), Open Government Data (data.wien.gv.at), Municipal Department 45- Water Management Vienna, GeoSphere Austria, BOKU University, University of Vienna. Map Author: Constanze Englisch.

Fig. 1: The city of Vienna, with its boundaries outlined in black. Sampling sites are indicated by circles. Hydrogeological zones are shown using colour-coded background areas representing the main continuous aquifers. The fill colour of the circles indicates the local aquifer type at each sampling site (local hydrogeology or main hydrogeological zone). | **Abb. 1:** Die Stadt Wien und ihre Stadtgrenzen (schwarze Linie). Die Probennahmepunkte sind als Kreise dargestellt. Die unterschiedlichen Grundwasserleiter sind farblich unterschieden und so auch die Zugehörigkeit der einzelnen Probennahmepunkte zu den hydrogeologischen Einheiten.

is pronounced spatial variability, ranging from up to 800 mm annually in the Wienerwald to less than 600 mm in parts of the southeast. These climatic gradients, together with the city's mosaic of urbanized areas, extensive protected landscapes, and heterogeneous hydrogeology, create diverse environmental conditions that make Vienna well suited for studying groundwater ecosystems, the distribution of groundwater fauna, and its ecological responses to anthropogenic pressures.

Groundwater sampling, on-site measurements and fauna collection

Two comprehensive groundwater sampling campaigns were conducted in autumn 2021 (September – December) and spring 2022 (February – April) collecting fauna from 163 groundwater observation wells distributed citywide. Sites were selected based on geology/aquifer types and availability (Fig. 1). Fauna was sampled with a miniaturized Cvetkov net (100 μm mesh; weighted angling mechanism with 50 mL tube; Jäger et al. 2022). Samples were preserved in ethanol ($\geq 70\%$ final conc.). Targeted resampling of selected wells in June 2023 provided fresh material for sequencing, this time immediately preserved in molecular grade EtOH (96%) and stored at -80°C .

For physical-chemical and microbiological analysis, each well was purged 2–3 times with a submersible pump (Grundfos MP1; Eijkelpoort Soil & Water, Giesbeek, Netherlands) to remove stagnant well water before collecting fresh groundwater samples. On-site we measured groundwater temperature, dissolved oxygen, electrical conductivity, and pH with field sensors (Multi 3620; WTW, Weilheim, Germany), and recorded the depth to the groundwater table (distance between ground surface and water level), well depth, and water column height. Water samples dedicated to DOC/DIC analysis were filtered on-site through 0.45 μm syringe filters into muffled 40 mL glass vials, with DOC samples further acidified to pH 2 using HCl. All samples were stored at 8°C in darkness until processing.

Laboratory analysis

Abiotic and microbial analyses

Collected water samples were analyzed for its stable water isotopes signature (D/H, $^{18}\text{O}/^{16}\text{O}$) and electrical conductivity to evaluate the surface water influence (Kaminsky et al. 2025a). Based on its hydrochemical composition, groundwater samples were categorized into four redox categories. These categories ranged from 1, indicating oxic conditions, to 4, indicating highly reduced conditions. A detailed description is found in Kaminsky et al. (2025a).

Concentrations of major ions and nutrients (NO_3^- , NO_2^- , NH_4^+ , PO_4^{3-} , SO_4^{2-} , Cl^- , Na^+ , K^+ , Ca^{2+} , Mg^{2+}), as well as ferrous iron (Fe^{2+}) and reduced manganese (Mn^{2+}) were determined after filtration through 0.45 μm membrane filters using ion chromatography (DIONEX ICS-1100; Thermo Fisher Scientific, Waltham, USA) and standardized photometric assays, respectively (Kaminsky et al. 2025a). Dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC) were measured using catalytic oxidation with non-dispersive infrared detection (Shimadzu TOC-L Analyzer, Shimadzu, Kyoto, Japan) (Kaminsky et al. 2025a). For chemical species with values below the detection limit, i.e. nitrate and ammonium, the detection limits of 0.04 mg/L for NO_3^- and 0.01 mg/L for NH_4^+ were used for statistical analysis.

Microbial activity in groundwater was assessed by means of intracellular ATP concentration in fresh groundwater samples using a luciferin-oxidation method with a luminometer plate reader (Promega, Madison, WI, USA) in triplicate. Total prokaryotic cell counts (TCC) were determined from glutaraldehyde fixed samples by means of flow cytometry in combination with SYBR Green staining (Amnis CellStream, Luminex, Austin, TX, USA) (Retter et al. 2021).

We measured the distance of all sampling points to the nearest surface water using the state map of Vienna (Open Data Austria 2024). Surface sealing was quantified as mean percent sealed area in the upstream zone of each well using triangular catchments extending 300 m upstream with a 120° opening, oriented by groundwater flow from isopiestic lines (GeoSphere Austria; Englisch et al. 2025, in revision). Mean imperviousness was extracted from the Copernicus Imperviousness Density HRL 2018 (10 × 10 m) and assigned to sites. For wells outside a continuous aquifer with no isopiestic lines, we used a circular area of radius 222.6 m (area 155,772 m²), following Böttcher & Zosseder (2022). Hydraulic conductivity (K_f) was extracted from a 10 × 10 m raster (GeoSphere Austria); gaps (isolated western wells) were filled using sediment distribution data (Grupe et al. 2021; Pfeiderer et al. 2019).

Taxonomic analysis of groundwater fauna

Prior to sorting, fauna samples fixed in EtOH were stained with eosin to enhance the visibility of small and unpigmented meiofauna. All specimens were then sorted into major taxonomic groups (phylum to order) under a stereomicroscope and morphologically identified to the lowest possible taxonomic level. Morphological identification of amphipods was genetically evaluated. Where the morphological and genetic identifications differed, specimens were re-examined morphologically for definite identification.

Barcoding of mitochondrial cytochrome c oxidase subunit I (COI) gene fragments from each morphotype (if possible, $n > 1$ from multiple sampling sites) confirmed or revised the morphological identification. Whole genomic DNA was extracted from one to several Speedvac-dried legs of each individual (Eppendorf, Hamburg, Germany) using a modified QIAamp UCP DNA Micro Kit (50) (QIAGEN, Hilden, Germany) Quick-Start Protocol (step 1: 100 µL AUT buffer; step 4: 56 °C for 10–14 h; step 2: reuse of 20 µL initial eluate). Partial mtCOI amplification was done using the primers LCO1490/HCO2198 (Folmer et al. 1994). 50 µL standard reactions with 0.5–2 µL template (Q5 High-Fidelity DNA Polymerase, New England Biolabs, USA) were run following Geller et al. (2013) (5' 95 °C; 35 x (30" 95 °C, 30" 48 °C, 45" 72 °C); 5' 72 °C) and visualized using SYBR (SYBR Safe/Gold; Thermo Fisher Scientific) after electrophoretic separation in agarose gels. Products were Sanger-sequenced with Microsynth Austria GmbH. *Phred* (Ewing & Green 1998; Ewing et al. 1998) and *Geneious* (Kearse et al. 2012) were used to process raw chromatograms. We BLASTed sequences against NCBI for confirmation of identifications (Altschul et al. 1990). The final alignment (E-INS-I MAFFT; Katoh & Toh 2008; Katoh & Standley 2013) contained the new COI sequences and reference data (Weber et al. 2022: *Niphargus* aff. *aquilex* NCBI OK380849; Griebler et al. 2023b) and was used to infer phylogenetic relationships via IQTREE (Nguyen et al. 2015) estimating branch support through UFBoot (Minh et al. 2013), aBayes (Anisimova et al. 2011), and SH-aLRT (Guindon et al. 2010). The resulting tree was visualized with iTOL (Letunic & Bork 2021), with isopods serving as the outgroup. All sequences can be accessed at GenBank PZ503198 to PZ503226.

Statistical Analyses

Statistical analyses and visualizations were done in R (R Core Team 2021) via RStudio 2023.9.1.494 (Posit Team 2023) using the packages *vegan* (Oksanen et al. 2022), *tidyr* (Wickham & Girlich 2022), *DescTools* (Signorell et al. 2022), *ggplot2* (Wickham 2016), *reshape2* (Wickham 2007), *FSA* (Ogle et al. 2023), *TOSTER* (Lakens 2017; Caldwell 2022). An Akaike Information Criterion (AIC)-based permutational multivariate analysis of variance (PERMANOVA) approach was done using the code from kdyson (2017). GIS analyses and visualizations were done in QGIS 3.22.11 (QGIS Development Team 2024). The significance threshold was set at $p < 0.05$; p-values adjustment used a False Discovery Rate (FDR; Benjamini & Hochberg 1995) approach.

Community composition and associated environmental drivers

We included only taxa occurring in >5 samples and pooled subspecies (i.e. of *Nitocrella hirta*) at the species level. After preselecting environmental variables to reduce noise/multicollinearity, the community matrix was log- and then Hellinger-transformed and Bray–Curtis dissimilarities were computed. Continuous predictors were screened with Mantel tests and categorical ones with ANOSIM; significant variables were checked for multicollinearity via Spearman, retaining proxies (e.g., electrical conductivity for major ions; dissolved oxygen for redox). The final PERMANOVA analysis set comprised electrical conductivity, geology/aquifer type, groundwater temperature, surface-water influence, and dissolved oxygen; the best model was chosen using an adapted AIC, and variable order was set by R^2 , single-variable AIC, and ecological relevance (geology/aquifer > dissolved oxygen > surface-water influence). Community patterns were visualized with NMDS in two runs (all samples; outliers removed), with outliers defined as distances from the NMDS centroid above the 95th percentile.

Environmental drivers of crustacean occurrence and distribution in the shallow aquifers

We classified samples into presence versus absence groups (amphipods; extended to Bat-hynellacea, Cyclopoida, Harpacticoida, Isopoda, Ostracoda). Continuous variables were visualized with boxplots (log-scaled y where appropriate) and tested using the two-sample Brunner–Munzel permutation test (10,000 permutations; robust to unequal variances/sample sizes). Categorical variables were evaluated by comparing observed versus expected counts under the null hypothesis of no effect, with significance from G-tests. Cladocera were excluded due to the occurrence of a single specimen ($n=1$).

Species-specific environmental associations in amphipods

Environmental affinities among amphipod species were assessed using continuous variables based on sample presence, including a “no Amphi” category. Differences were tested with Kruskal–Wallis rank sum tests followed by Dunn’s post hoc tests. Boxplots (log-scaled y where appropriate) display selected ecologically relevant variables with significant interspecific differences. Categorical variables were analyzed using pairwise Fisher’s exact tests. A map illustrating the spatial distribution of amphipod species across Vienna was generated.

Results

Crustacean diversity in Vienna's groundwater

A broad diversity of stygobiont and stygophile crustaceans was detected across Vienna. Of the 306 groundwater fauna samples, amphipods occurred in 100 samples, whereas crustaceans in general were detected in 220. Bathynellacea occurred in 13 samples, Cyclopoida in 123, Harpacticoida in 18, Isopoda in 95, Ostracoda in 128, and Cladocera in only a single sample. In 27 samples, no fauna was detected at all, considering all fauna groups, not only crustaceans (Fig. 2 & 3).

When resolved taxonomically, these records comprised a total of 47 taxa representing 23 genera and 15 families, including three undescribed *Nitrocrella hirta* subspecies (Santiago Gaviria-Melo pers. comm.; detailed morphological differences are listed in the supplementary material) (Tab. 1).

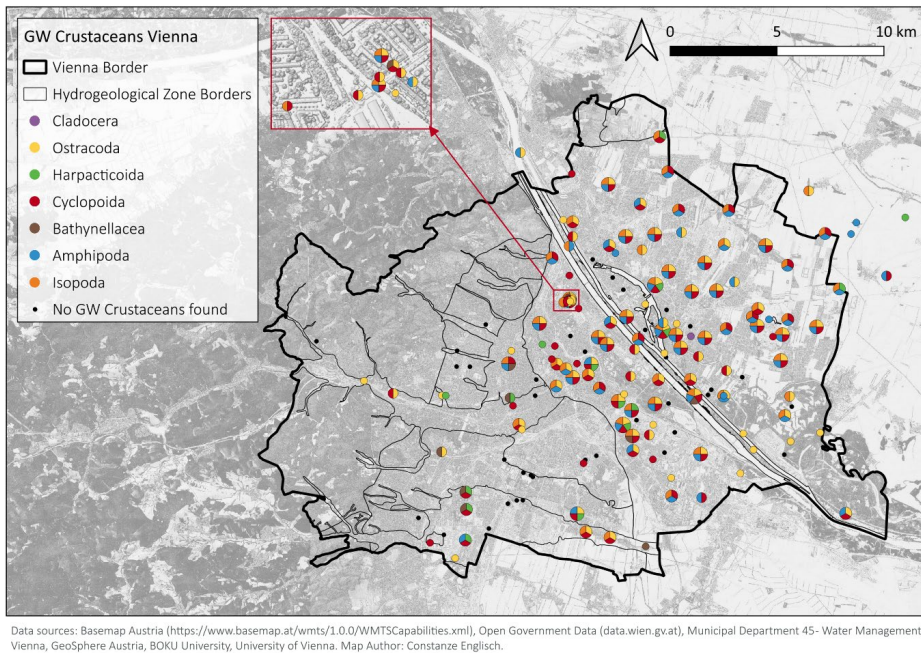


Fig. 2: Spatial distribution of crustacean groups (including stygophile and stygobiont taxa) across the study area in Vienna. Each point represents a sampled site. At sites where crustaceans were found, pie charts indicate the occurrence of the different groups, with colours corresponding to the respective group. Sites without crustaceans are shown as simple black points. Fine black lines indicate the borders of the major hydrogeological zones in Vienna which are depicted in detail in Figure 1. | **Abb. 2:** Räumliche Verteilung der einzelnen Crustaceengruppen unter Wien, stygophile und stygobionte Taxa. Jedes Symbol repräsentiert einen Probenahmepunkt. Das Auftreten einzelner Großgruppen ist in Form von Tortendiagrammen dargestellt. Standorte die keine Crustaceennachweise lieferten sind als einfach schwarze Punkte dargestellt. Dünne schwarze Linien sind Grenzen der hydrogeologischen Zonen. Siehe auch Abb. 1.

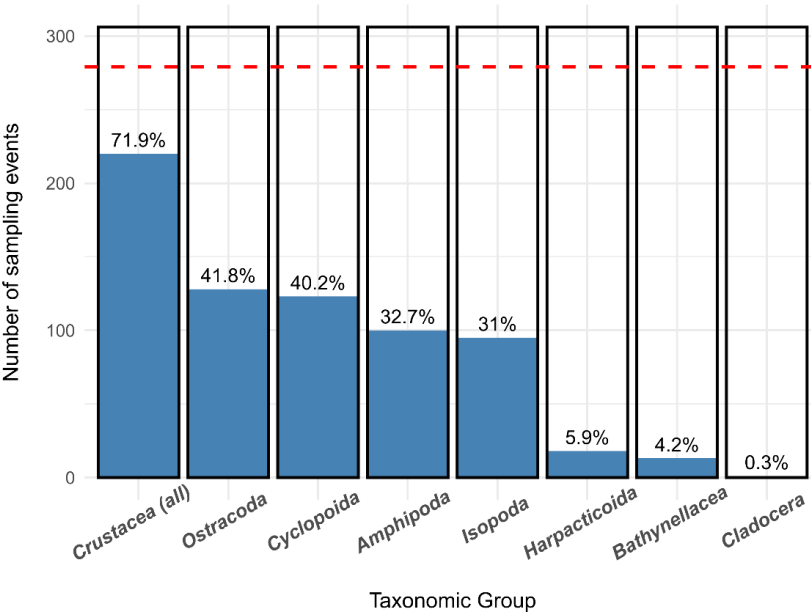


Fig. 3: Occurrence of taxonomic groups across 306 samples. The bar chart shows the number of samples in which each taxonomic group was detected, with percentage values above the bars relative to the maximum of 306 samples. Groups are sorted by frequency of occurrence. The red dashed line marks the 27 samples with a complete absence of fauna, including non-crustacean groups. | **Abb. 3:** Auftreten der taxonomischen Großgruppen. Das Säulendiagramm zeigt in wievielen Proben (aus 306) Vertreter einzelner Gruppen gefunden wurden. Die taxonomischen Gruppen sind absteigend nach Häufigkeit des Auftretens geordnet. Die rote gestrichelte Linie markiert die 27 Proben die keine Fauna enthielten.

Tab. 1: List of stygobiont and stygophile taxa identified in Vienna, based on data from the sampling campaigns conducted in 2021 and 2022. | **Tab. 1:** Liste aller in den Jahren 2021 und 2022 in Wiens Grundwasser gefundenen Crustaceen.

CLASS	ORDER	FAMILY	TAXA
Branchiopoda	Cladocera	Chydoridae	<i>Peracantha truncata</i> (O. F. Müller, 1785)
Ostracoda	Podocopida	Candonidae	<i>Cryptocandona kieferi danubialis</i> Namiotko et al. 2005
			<i>Marmocandona zschokkei</i> (Wolf, 1920)
			<i>Mixtacandona laisi</i> (Klie, 1938)
			<i>Mixtacandona spandli</i> Rogulj & Danielopol, 1993
			<i>Mixtacandona transleithanica</i> (Löffler, 1960)
			<i>Pseudocandona lobipes</i> (Hartwig, 1900)
			<i>Schellencandona belgica</i> (Klie, 1937)
			<i>Typhlocypris eremita</i> (Vejdovsky, 1882)
		Cyprididae	<i>Heterocypris incongruens</i> (Ramdohr, 1808)
		Limnocytheridae	<i>Kovalevskiella elisabethae</i> Gaviria, 2022

CLASS	ORDER	FAMILY	TAXA
Copepoda	Harpacticoida	Ameiridae	<i>Nitocra</i> n. sp.
			<i>Nitocrella hirta hirta</i> (Chappuis, 1924)
			<i>Nitocrella hirta</i> ssp. 1
			<i>Nitocrella hirta</i> ssp. 2
			<i>Nitocrella hirta</i> ssp. 3
		Chappuisiidae	<i>Chappuisius inopinus</i> Kiefer, 1938
		Parastenocarididae	<i>Fontinalicaris fontinalis borea</i> (Kiefer, 1960)
			<i>Fontinalicaris fontinalis fontinalis</i> (Schnitter & Chappuis, 1915)
			<i>Parastenocaris gertrudae</i> Kiefer, 1968
			<i>Parastenocaris husmanni</i> Chappuis, 1953
		Phyllognathopodidae	<i>Phyllognathopus viguieri</i> (Maupas, 1892)
	Cyclopoida	Cyclopidae	<i>Acanthocyclops gmeineri</i> Pospisil, 1989
			<i>Acanthocyclops hispanicus</i> Kiefer, 1937
			<i>Acanthocyclops kieferi</i> (Chappuis, 1925)
			<i>Acanthocyclops rhenanus</i> Kiefer, 1936
			<i>Acanthocyclops sensitivus</i> (Graeter & Chappuis, 1914)
			<i>Acanthocyclops venustus</i> (Norman & Scott, 1906)
			<i>Diacyclops charon</i> (Kiefer, 1931)
			<i>Diacyclops cohabitatus</i> Monchenko, 1980
			<i>Diacyclops danielopoli</i> Pospisil & Stoch, 1999
			<i>Diacyclops felix</i> Pospisil & Stoch, 1999
			<i>Diacyclops languidoides goticus</i> Kiefer, 1931
			<i>Diacyclops languidoides languidoides</i> (Lilljeborg, 1901)
			<i>Eucyclops graeteri</i> (Chappuis, 1927)
			<i>Paracyclops fimbriatus</i> (Fischer, 1853)
			<i>Paracyclops imminutus</i> Kiefer, 1929
Malacostraca	Bathynellacea	Bathynellidae	<i>Bathynellidae</i> gen. sp.
		Parabathynellidae	<i>Parabathynellidae</i> gen. sp.
	Amphipoda	Bogidiellidae	<i>Bogidiella albertimagni</i> Hertzog, 1933
		Crangonyctidae	<i>Crangonyx subterraneus</i> (Bate, 1859)
		Niphargidae	<i>Niphargus</i> aff. <i>aquilex</i> Schiødte, 1855
			<i>Niphargus bajuvaricus</i> Schellenberg, 1932
			<i>Niphargus caspary</i> (Pratz, 1866)
			<i>Niphargus inopinatus</i> Schellenberg, 1932
			<i>Niphargus tonywhitteni</i> Fišer et al. 2018
	Isopoda	Asellidae	<i>Proasellus slavus</i> (Remy, 1948)



Fig. 4: Phylogenetic tree based on COI sequences from amphipod species sequenced in this study (coloured by species), alongside isopod sequences (outgroup), amphipod sequences from a previous study (Griebler et al. 2023b), and one additional *Niphargus* aff. *aquilex* sequence from Luxembourg (Weber et al. 2022). Species from this study (coloured) are described by species name followed by the project title (HBT C = 'Heat below the City'), and a project-specific consecutive well number. Several published sequences were collapsed into clusters for clarity, with the species included in each cluster indicated alongside the number of sequences per species in parentheses. Well-supported branches are marked by orange circles (UFBoot $\geq 95\%$, aBayes ≥ 0.9 , SH-aLRT $\geq 85\%$), with circle size proportional to support strength. | **Abb. 4:** Phylogenetischer Baum auf Basis von COI Sequenzen für ausgewählte Amphipoden aus der Projektstudie. Zusätzlich wurden Sequenzen aus vorangehenden Untersuchungen im Raum Wien (Griebler et al. 2023) berücksichtigt und eine Sequenz von *Niphargus* aff. *aquilex* aus Luxemburg (Weber et al. 2022). Die Arten aus dem Projekt sind farblich markiert und der Code setzt sich aus Artnamen gefolgt vom Projektkürzel (HBT C = Heat below the City) und fortlaufender Standortnummer zusammen. Weitere publizierte Amphipodenarten sind im Baum als Cluster (mehrere Arten zusammengefasst) integriert. Äste mit gut dokumentierten Arten sind durch einen orangen Kreis markiert (UFBoot $\geq 95\%$, aBayes ≥ 0.9 , SH-aLRT $\geq 85\%$).

Taxonomic richness and composition varied among groups: Cyclopoida were richest (15 taxa in a single family); Harpacticoida had eleven taxa across four families (highest family diversity); Ostracoda exhibited ten taxa from three families, dominated by Candonidae (8/10); Amphipoda comprised seven taxa of three families, with Niphargidae dominating (5/7); Bathynellacea included at least two taxa from two families, i.e. Bathynellidae and Parabathynellidae. Both Isopoda and Cladocera were each represented by a single taxon.

Stygobiont amphipods in the shallow aquifers of Vienna

Most amphipod species collected showed consistent morphological, BLAST, and phylogenetic results (*Bogidiella albertimagni*, *Crangonyx subterraneus*, *Niphargus bajuvaricus*, *Niphargus caspary*, and most specimens of *Niphargus inopinatus*). In this respect, molecular analyses largely confirmed expert-based morphological identifications, with only a few exceptions. Some individuals were reassigned based on molecular evidence: specimens identified as *Niphargus* cf. *fontanus* were confirmed as *Niphargus tonywhitteni*, and several specimens initially suspected to belong to *Niphargus laisi* were genetically identified as *N. inopinatus*. One taxon, morphologically identified as *Niphargus aquilex*, could not be confidently assigned to any described species and is therefore referred to as *N. aff. aquilex*. BLAST searches revealed no close genetic matches except for a single, likewise unresolved *N. aff. aquilex* sequence from Luxembourg (Weber et al. 2022, Accession Number: OK380849; NCBI). Phylogenetic analyses placed this lineage clearly apart from *N. aquilex* and other published *N. aff. aquilex* lineages, indicating an unresolved taxonomic status (Fig. 4). Overall, the phylogenetic tree shows that amphipod sequences generated in this study cluster with sequences of the same species from previous studies, reflecting clear species-level groupings. Throughout this paper, the spelling *Niphargus caspary* is used, although both *N. caspary* and *N. casparyi* occur in the literature and the correct orthography remains unresolved.

Environmental structuring of crustacean community composition

The final PERMANOVA model revealed geology/aquifer type, dissolved oxygen concentration and surface water influence as the most important explanatory variables for differences in groundwater crustacean community compositions (Tab. 2).

Tab. 2: Results of the Permutational Multivariate Analysis of Variance (PERMANOVA) for the ecological variables geology/aquifer type, dissolved oxygen concentration, and surface water influence. The analysis is based on 999 permutations. | **Tab. 2:** Ergebnisse der PERMANOVA für die ökologischen Variablen Geologie/Aquifertyp, gelöster Sauerstoff und Oberflächenwassereinfluss. Die Analyse basiert auf 999 Permutationen.

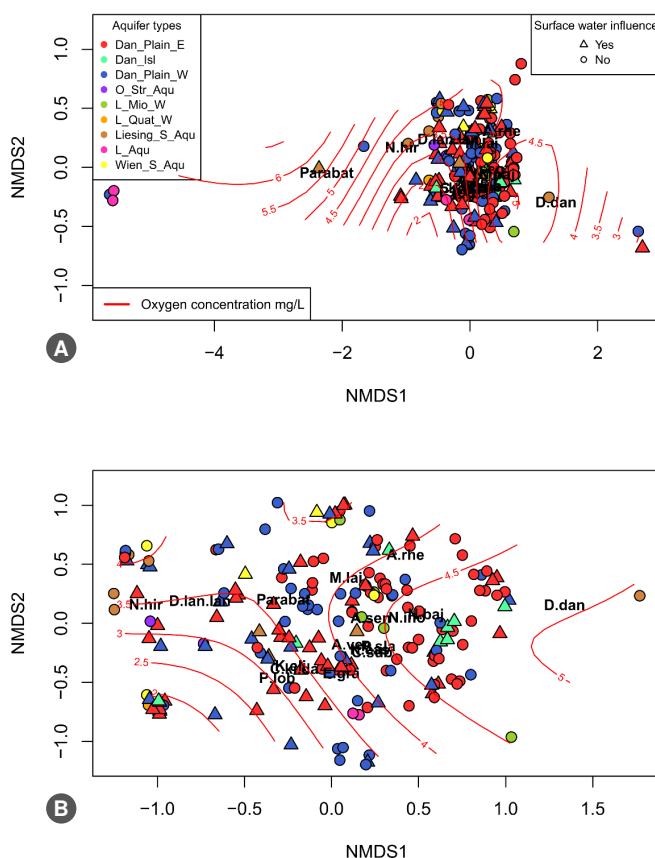
Ecological parameter	df	SumOfSqs	MeanSqs	R ²	F	p-value
Geology/Aquifer type	8	7.377	0.9221	0.10558	3.0090	0.001
Dissolved oxygen (mg/L)	1	1.743	1.7430	0.02494	5.6863	0.001
Surface water influence	1	1.608	1.6080	0.02301	5.2465	0.001
Residual	193	59.143	0.3064	0.84647		
Total	203	69.870		1.00000		

Fig. 5: Non-metric Multidimensional Scaling (NMDS) ordination of crustacean community composition. (A) Ordination including all samples. (B) Ordination excluding identified outliers. Points represent individual samples and are coloured by aquifer type. Surface water influence is indicated by point shape. Dissolved oxygen concentration is shown as smooth red isolines fitted across the ordination. Weighted average species scores are overlaid in black. Stress values: 0.1346 (A) and 0.1741 (B).

Taxa abbreviations: N.cas = *Niphargus caspary*, N.baj = *Niphargus bajuvaricus*, N.ino = *Niphargus inopinatus*, C.sub = *Crangonyx subterraneus*, A.rhe = *Acanthocyclops rhenanus*, A.sen = *Acanthocyclops sensitivus*, A.ven = *Acanthocyclops venustus*, D.dan = *Diacyclops danielopolis*, D.lan.lan = *Diacyclops languidoides languidoides*, E.gra = *Eucyclops graeteri*, C.ki.da = *Cryptocandona kieferi danubialis*, M.lai = *Mixtacandona laisi*, P.lob = *Pseudocandona lobipes*, K.eli = *Kovalevskiella elisabethae*, Parabat = *Parabathynellidae* gen. sp., N.hir = *Nitocrella hirta*, P.sla = *Proasellus slavus*.

Aquifer type abbreviations: Dan_Plain_E = Danube Plain East, Dan_Plain_W = Danube Plain West, Dan_Isl = Danube Island, O_Str_Aqu = Other Stream Aquifer, L_Mio_W = Local Miocene Water, L_Quat_W = Local Quaternary Water, Wien_S_Aqu = Wien Stream Aquifer, Liesing_S_Aqu = Liesing Stream Aquifer, L_Aqu = Local Aquifer (see Fig. 1).

Abb. 5: NMDS Ordination der Crustaceengemeinschaften. (A) Ordination inklusive aller Proben. (B) Ordination exklusive einzelner Ausreißer. Die Symbole repräsentieren individuelle Proben und sind entsprechend ihrer Zugehörigkeit zu den Aquifertypen gefärbt. Der Oberflächenwassereinfluss ist durch die Form der Symbole repräsentiert. Die Konzentrationen an gelöstem Sauerstoff sind als rote Isolinen in das Ordinationsdiagramm eingefügt. Gewichtete durchschnittliche Werte für einzelne Arten sind in schwarzer Schrift eingefügt. Stresswerte: 0.1346 (A) und 0.1741 (B). **Abkürzungen für die Taxa:** N.cas = *Niphargus caspary*, N.baj = *Niphargus bajuvaricus*, N.ino = *Niphargus inopinatus*, C.sub = *Crangonyx subterraneus*, A.rhe = *Acanthocyclops rhenanus*, A.sen = *Acanthocyclops sensitivus*, A.ven = *Acanthocyclops venustus*, D.dan = *Diacyclops danielopolis*, D.lan.lan = *Diacyclops languidoides languidoides*, E.gra = *Eucyclops graeteri*, C.ki.da = *Cryptocandona kieferi danubialis*, P.lob = *Pseudocandona lobipes*, K.eli = *Kovalevskiella elisabethae*, Parabat = *Parabathynellidae* gen. sp., N.hir = *Nitocrella hirta*, P.sla = *Proasellus slavus*. **Abkürzungen für Aquifertypen:** Dan_Plain_E = Danube Plain East, Dan_Plain_W = Danube Plain West, Dan_Isl = Danube Island, O_Str_Aqu = Other Stream Aquifer, L_Mio_W = Local Miocene Water, L_Quat_W = Local Quaternary Water, Wien_S_Aqu = Wien Stream Aquifer, Liesing_S_Aqu = Liesing Stream Aquifer, L_Aqu = Local Aquifer (siehe Abb. 1).



Geology/aquifer type explained the largest proportion of variation ($R^2 = 0.106$, $F = 3.01$, $p = 0.001$), making it the strongest predictor in the best-fitting model. Dissolved oxygen concentration ($R^2 = 0.025$, $F = 5.69$, $p = 0.001$) and surface water influence ($R^2 = 0.023$, $F = 5.25$, $p = 0.001$) also showed significant but smaller effects, with dissolved oxygen emerging as the slightly stronger of the two. Despite these significant relationships, most variation in community composition remained unexplained (residual $R^2 = 0.846$), suggesting that additional disregarded environmental factors and/or stochastic processes likely contribute to the observed community differences. Notably, sampling season (autumn vs. spring) did not have a significant effect.

Community-level patterns and environmental gradients were further explored using NMDS ordination, incorporating the three variables identified in the PERMANOVA (Fig. 5). Stress values were 0.1346 (including outliers) and 0.1741 (excluding outliers), both indicating an acceptable representation of the underlying dissimilarity structure. The NMDS ordinations revealed a dense central cluster encompassing the majority of samples, accompanied by a small number of distinct outliers. Samples associated with *Diacyclops danielopolis* were positioned toward the positive end of the NMDS1 axis, whereas those linked to *Parabathynellidae* gen. sp. occurred toward negative NMDS1 values. Following removal of outliers, *Parabathynellidae* gen. sp. shifted slightly toward the central cluster, while the overall spatial configuration of the different samples remained largely unchanged. Across aquifer types, no distinct groupings or clearly separated community clusters were evident in the NMDS ordinations. Samples from different aquifer types overlapped strongly when outliers were included. Outlier events originated from multiple aquifer types. Only *Parabathynellidae* gen. sp., *Diacyclops danielopolis*, and *Nitocrella hirta* appeared spatially associated with individual samples from the Liesing Stream Aquifer. After excluding outliers, the general lack of well-defined clustering persisted, however, more subtle spatial patterns became discernible. Samples from the Danube Plain aquifer (east and west) remained broadly scattered throughout the ordination space, while samples from the Danube Island were mainly aligned along the positive NMDS1 axis and occurred in proximity to the species scores of *Niphargus bajuvaricus* and *Niphargus inopinatus*. Samples from the Liesing Stream Aquifer were situated mainly in the negative NMDS1 region, with NMDS2 values approximately around zero. Samples from the Wien Stream Aquifer were concentrated primarily in the positive NMDS2 and negative NMDS1 region.

Regarding dissolved oxygen concentration, the NMDS ordination, including outliers, revealed a gradient with a range of approximately 2.5–5.5 mg/L, with *Parabathynellidae* gen. sp. associated with the highest oxygen levels. Due to the dense central clustering, finer patterns were easier to resolve after excluding outliers, but the overall range of the gradient remained almost unchanged. In this ordination, *D. danielopolis* was associated with the highest oxygen concentrations (≈ 5 mg/L). Several species including *M. laisi*, *A. rhenanus*, *A. sensitivus*, *A. venustus*, *E. graeteri*, *C. subterraneus*, *N. bajuvaricus*, *N. caspary*, *N. inopinatus*, and *P. slavus* were associated with intermediate oxygen levels (≈ 4.0 – 4.5 mg/L), whereas lower oxygen concentrations (≈ 3.0 – 3.5 mg/L) were linked to *C. kieferi danubialis*, *P. lobipes*, *K. elisabethae*, *D. languidoides languidoides* and *N. hirta*. *Parabathynellidae* gen. sp., previously among the high oxygen samples, shifted toward the central cluster after outlier removal, corresponding to moderate oxygen levels (≈ 3.5 mg/L).

Surface water influence did not produce a distinct structure within the main cluster when outliers were included, while outlier samples were mostly not affected by surface water. After excluding outliers, a moderate separation became apparent, with surface water influenced samples occurring predominantly in the negative quadrant of the NMDS plot, where *P. lobipes*, *C. kieferi danubialis*, and *K. elisabethae* were positioned.

Overall, compositional tendencies were detectable for all three variables, which may reflect the PERMANOVA results. However, the NMDS ordinations indicate a largely homogeneous community structure, and clearly separated community clusters based on these variables were not observed.

Environmental drivers shaping the occurrence and distribution of amphipods and other crustaceans

Presence-absence patterns of total Crustacea and individual crustacean groups were analysed in relation to environmental variables. After False Discovery Rate (FDR) correction, seven continuous parameters emerged as significant for Amphipoda (Fig. 6) and eight for total Crustacea, with largely overlapping sets of predictors. Both Amphipoda and total Crustacea preferably occurred in samples with higher dissolved oxygen concentrations (Amphipoda: $p < 0.001$; total Crustacea: $p < 0.001$) and lower values of microbial activity (ATP; Amphipoda: $p < 0.001$; total Crustacea: $p < 0.001$), bacterial abundance (TCC; Amphipoda: $p < 0.001$; total Crustacea: $p < 0.001$), dissolved organic carbon (DOC; Amphipoda: $p = 0.002$; total Crustacea: $p = 0.006$), ammonium (Amphipoda: $p < 0.001$; total Crustacea: $p = 0.001$), and ferrous iron (Amphipoda: $p < 0.001$; total Crustacea: $p < 0.001$), compared to samples where they were absent. Amphipoda additionally occurred more frequently at significantly lower temperatures ($p = 0.006$), whereas this pattern was not observed for total Crustacea. However, no crustaceans were found at temperatures above 21.94°C. In contrast, total Crustacea showed significant associations with lower dissolved inorganic carbon (DIC; $p = 0.043$) and higher nitrate concentrations ($p = 0.019$), relationships that were not significant for Amphipoda.

For the remaining crustacean groups, many of the directional patterns observed for Amphipoda and total Crustacea were likewise evident. Dissolved oxygen concentrations were consistently higher in samples containing Bathynellacea ($p = 0.001$), Cyclopoida ($p < 0.001$), Harpacticoida ($p < 0.001$), and Isopoda ($p < 0.001$). Microbial activity (ATP), bacterial abundance (TCC), and DOC were lower at sites where Cyclopoida (ATP: $p = 0.001$; TCC: $p = 0.029$; DOC: $p < 0.001$) and Isopoda (ATP: $p < 0.001$; TCC: $p < 0.001$; DOC: $p = 0.038$) occurred. Nitrate showed the same positive association as in the total Crustacea analysis with higher concentrations in samples containing Isopoda ($p = 0.002$), Harpacticoida ($p = 0.035$), and Cyclopoida ($p < 0.001$). Ammonium concentrations were lower at sites where Bathynellacea ($p < 0.001$), Cyclopoida ($p < 0.001$), and Isopoda ($p < 0.001$) were present, and ferrous iron likewise showed a negative association with the occurrence of Cyclopoida ($p < 0.001$) and Isopoda ($p < 0.001$).

Beyond these shared patterns, several significant relationships were restricted to individual crustacean groups. Water column height was negatively associated with Bathynellacea ($p = 0.019$), Harpacticoida ($p = 0.013$), and Cyclopoida ($p < 0.001$). Hydraulic conductivity

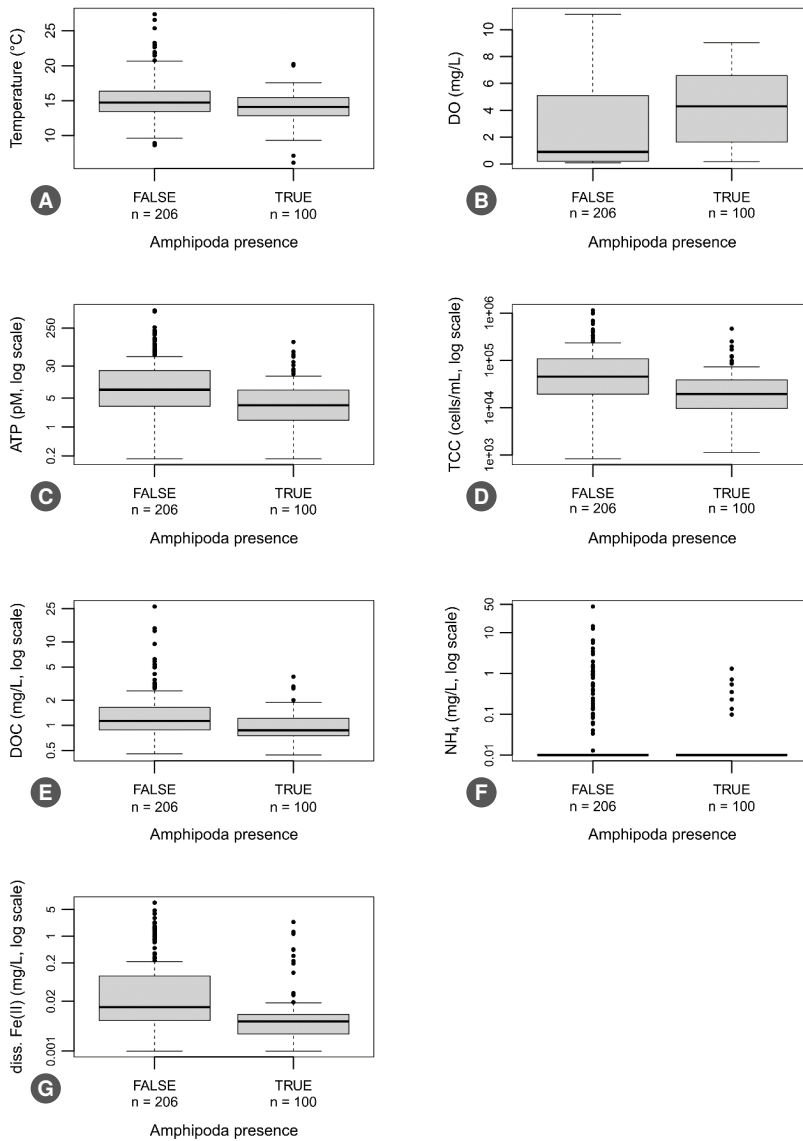


Fig. 6: Boxplots of continuous environmental variables that showed significant associations with Amphipoda presence across all samples (“FALSE” = absent, “TRUE” = present). Plots display median, interquartile range (IQR), whiskers (1.5 × IQR), and outliers. Variables: A) groundwater temperature (Temperature), B) dissolved oxygen (DO). Variables with log-scaled y-axes: C) microbial activity (ATP), D) bacterial abundance (TCC), E) dissolved organic carbon (DOC), F) ammonium (NH₄⁺), and G) ferrous iron (diss. Fe²⁺). | **Abb. 6:** Boxplots von Umweltvariablen die einen signifikanten Zusammenhang mit der Anwesenheit von Amphipoden zeigen (“FALSE” = abwesend, “TRUE” = anwesend). Die Abbildungen zeigen Medianwerte, den interquartilen Bereich (IQR), Whiskers (1.5 × IQR), und Ausreißer. Variablen: A) Grundwassertemperatur (Temperature), B) gelöster Sauerstoff (DO), C) mikrobielle Aktivität (ATP), D) Gesamtbakterienzahl (TCC), E) gelöster organischer Kohlenstoff (DOC), F) Ammonium (NH₄⁺), und G) reduziertes Eisen (diss. Fe²⁺).

was negatively associated with Bathynellacea ($p = 0.013$) and Harpacticoida ($p = 0.035$), while surface sealing was positively associated with Harpacticoida ($p = 0.036$). Sulfate concentrations were positively associated with Harpacticoida ($p = 0.020$) and Cyclopoida ($p = 0.037$) and negatively with Ostracoda ($p = 0.014$). Chloride was positively associated with Harpacticoida ($p = 0.013$), and calcium positively with Harpacticoida ($p = 0.035$) but negatively with Ostracoda ($p = 0.036$). Magnesium ($p = 0.014$) and electrical conductivity ($p = 0.048$) were negatively associated with Ostracoda. Orthophosphate, sodium, potassium, and distance to surface water were positively associated with Cyclopoida ($p = 0.037$; $p = 0.037$; $p = 0.037$; $p < 0.001$).

In addition to continuous variables, three categorical environmental variables – surface water influence, geology/aquifer type, and redox conditions – were analysed. Surface water influence was only significant for Ostracoda, which exhibited higher-than-expected occurrences at sites classified as influenced by surface water ($p = 0.036$).

Geology/aquifer type showed no significant associations for total Crustacea, whereas Amphipoda exhibited significant differences. Amphipod occurrences were higher than expected in the Danube Plain East ($p = 0.046$) and Danube Island ($p = 0.046$) aquifers, and lower than expected in the Liesing Stream Aquifer ($p = 0.046$) and the Wien Stream Aquifer ($p = 0.046$). Bathynellacea showed lower-than-expected occurrences in the Danube Plain East aquifer ($p = 0.002$) but higher-than-expected occurrences in the Liesing Stream Aquifer ($p = 0.002$) and Local Aquifers ($p = 0.006$), while Isopoda exhibited lower-than-expected occurrences in the Local Miocene Water aquifer type ($p = 0.025$).

Redox conditions showed significant effects on most groups. For reference, redox categories were defined as: 1 = $O_2 > 2 \text{ mg/L}$; 2 = $O_2 < 2 \text{ mg/L}$; 3 = $Mn^{2+} > 0.1 \text{ mg/L}$ or $Fe^{2+} > 0.1 \text{ mg/L}$; 4 = $HS^- > 0.01 \text{ mg/L}$. Redox category 1 was associated with higher-than-expected occurrences (Amphipoda: $p = 0.005$; total Crustacea: $p < 0.001$; Cyclopoida: $p = 0.001$; Isopoda: $p = 0.034$). From category 2 onwards, only significant negative associations were observed: category 2 showed lower-than-expected occurrences for total Crustacea ($p = 0.024$), category 3 for Amphipoda ($p = 0.004$), total Crustacea ($p < 0.001$), Cyclopoida ($p < 0.001$), Harpacticoida ($p = 0.032$), and Isopoda ($p < 0.001$), and category 4 for Amphipoda ($p = 0.039$), Cyclopoida ($p = 0.017$), and Isopoda ($p = 0.046$).

It should be noted that sample sizes across categories were highly uneven, as was also the case for the occurrence of the individual crustacean groups (Fig. 4). For geology/aquifer type, sample numbers ranged from $n = 2$ (Local Quaternary Water & Not Defined) to $n = 141$ (Danube Plain East), with intermediate values for Danube Plain West ($n = 95$), Danube Island ($n = 10$), Liesing Stream Aquifer ($n = 15$), Wien Stream Aquifer ($n = 7$), Local Aquifers ($n = 7$), Local Miocene Water ($n = 21$), and Other Stream Aquifers ($n = 6$). Redox categories were similarly unbalanced (category 1: $n = 163$, category 2: $n = 79$, category 3: $n = 58$, category 4: $n = 6$), whereas surface water influence classes were moderately balanced (no: $n = 184$; yes: $n = 122$). Results should therefore be interpreted with appropriate caution.

Amphipod species-specific associations with environmental conditions

The most frequently recorded species, based on presence per sample, was *Niphargus inopinatus* (n = 76), followed by *N. caspary* (26), *N. bajuvaricus* (15), *Crangonyx subterraneus* (6), *Bogidiella albertimagni* (4), *N. tonywhitteni* (3), and *N. aff. aquilex* (2), while samples without amphipods were included as “no Amphi” (n = 206). These differences in occurrence, together with the low sample size for some species, should be considered when interpreting the results.

Dissolved oxygen (DO) (Fig. 7A) and ferrous iron (Fe^{2+}) both differed significantly between groups (KW: DO $p < 0.001$, Fe^{2+} $p < 0.001$). Dunn’s test for multiple comparisons, however, identified significant differences only between sites without amphipods and those with *N. bajuvaricus* (DO: $p = 0.009$, Fe^{2+} : $p = 0.034$), *N. caspary* (Fe^{2+} : $p = 0.011$), and *N. inopinatus* (DO: $p < 0.001$, Fe^{2+} : $p < 0.001$). Fe^{2+} showed an inverse pattern to DO, with species associated with lower DO concentrations tending to also be associated with higher Fe^{2+} values. No significant differences were observed between individual species for these variables, although some moderate differences are visible in the plot.

Microbial activity (ATP) (Fig. 7B) and bacterial abundance (TCC) also varied significantly between species/groups (KW: ATP $p < 0.001$, TCC $p < 0.001$), with both variables exhibiting comparable patterns. Sites without amphipods had higher ATP and TCC values than those where *N. inopinatus* (ATP: $p < 0.001$, TCC: $p < 0.001$), *N. caspary* (ATP: $p = 0.007$, TCC: $p = 0.001$), *N. bajuvaricus* (ATP: $p = 0.015$, TCC: $p = 0.001$), and *Bogidiella albertimagni* (ATP: $p = 0.024$) were found. Additionally, a significant difference in microbial activity (ATP) was observed specifically between two species, namely *B. albertimagni*, which had the lowest median, and *N. aff. aquilex*, which had the highest, among all species ($p = 0.037$).

Similarly, water column height (Wco) (Fig. 7C) and well depth (Wede) differed significantly between groups (KW: Wco $p = 0.007$, Wede $p = 0.032$), showing similar patterns. Here, most significant pairwise differences occurred between species. *B. albertimagni* exhibited the highest median values and differed from *N. aff. aquilex* (Wco: $p = 0.023$, Wede: $p = 0.030$), *N. tonywhitteni* (Wco: $p = 0.013$, Wede: $p = 0.041$), and “no Amphi” (Wco: $p = 0.049$, Wede: $p = 0.048$). Significant pairwise differences specific to water column height were also observed for *N. caspary*, which was associated with higher values than *N. tonywhitteni* ($p = 0.037$) and *N. aff. aquilex* ($p = 0.045$).

Hydraulic conductivity (K_f) (Fig. 7D) was significant overall (KW: $p = 0.034$), but no pairwise comparisons remained significant after FDR adjustment. Nevertheless, a gradient across species was apparent, with all species exhibiting higher K_f median values than “no Amphi,” except *C. subterraneus* and, notably, *N. aff. aquilex*, which was associated with particularly low values. Dissolved organic carbon (DOC) showed a significant KW result ($p = 0.001$). Subsequent Dunn’s test revealed only one significant difference: *N. inopinatus* was associated with lower DOC values than “no Amphi” ($p = 0.003$), while differences between other species were relatively minor. Electrical conductivity (EC) was not significant; however, it is worth mentioning that *N. aff. aquilex* exhibited a pronounced deviation with substantially higher values compared to other species. Similar patterns were observed for sulfate, chloride, sodium, and magnesium.

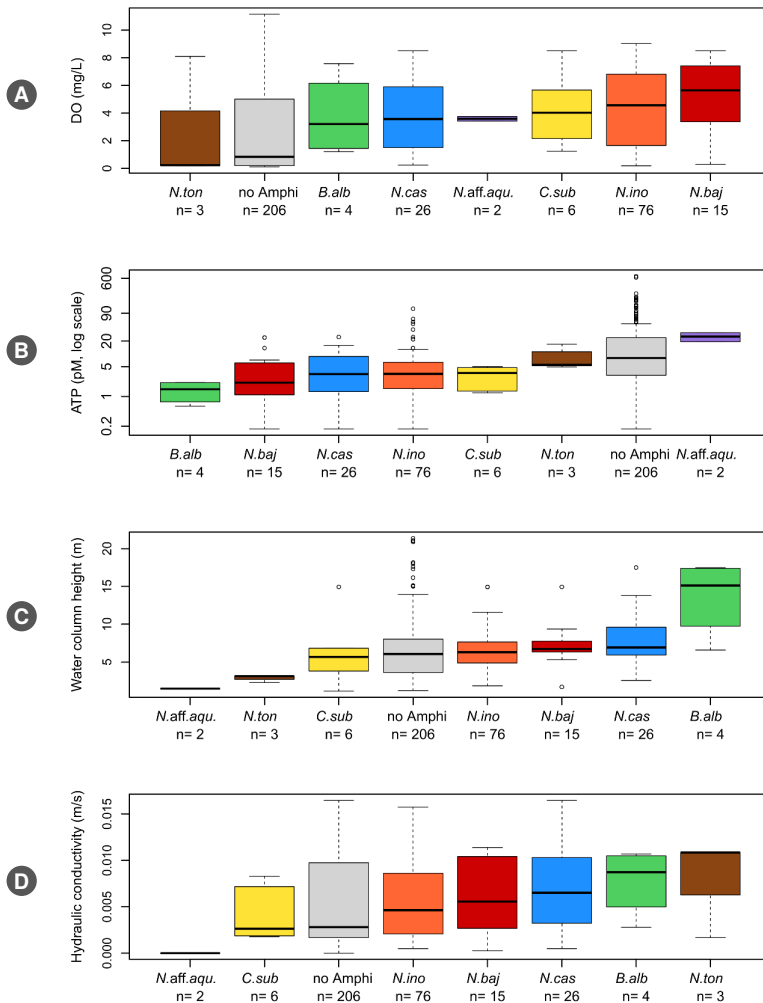


Fig. 7: Distribution of selected continuous environmental variables across all samples for different amphipod species and samples without amphipods (no Amphi). Panels show: (A) dissolved oxygen (DO), (B) microbial activity measured as cellular ATP, (C) water column height, and (D) hydraulic conductivity (K_f). The x-axis indicates amphipod species, labelled with the number of samples in which each species occurred, and the y-axis represents the respective parameter. Boxplots are arranged in order of increasing median. **Species abbreviations:** B.alb = *Bogidiella albertimagni*, C.sub = *Crangonyx subterraneus*, N.aff.aqu. = *Niphargus aff. aquilex*, N.baj = *Niphargus bajuvaricus*, N.cas = *Niphargus caspary*, N.ino = *Niphargus inopinatus*, N.ton = *Niphargus tonywhitteni*. “No Amphi” represents samples in which no amphipods were recorded. | **Abb. 7:** Variabilität ausgewählter Umweltfaktoren bei einzelnen Amphipodenarten im Vergleich zu den Standorten die keine Amphipoden (no Amphi) lieferten. Gezeigt sind: (A) gelöster Sauerstoff (DO), (B) mikrobielle Aktivität gemessen als intrazelluläres ATP, (C) Höhe der Wassersäule, und (D) hydraulische Leitfähigkeit (K_f). Die Amphipodenarten sind auf der x-Achse aufgetragen und entsprechend eines steigenden Medianwertes geordnet. **Abkürzung der Arten:** B.alb = *Bogidiella albertimagni*, C.sub = *Crangonyx subterraneus*, N.aff.aqu. = *Niphargus aff. aquilex*, N.baj = *Niphargus bajuvaricus*, N.cas = *Niphargus caspary*, N.ino = *Niphargus inopinatus*, N.ton = *Niphargus tonywhitteni*. “No Amphi” steht für Proben die keine Amphipoden enthielten.

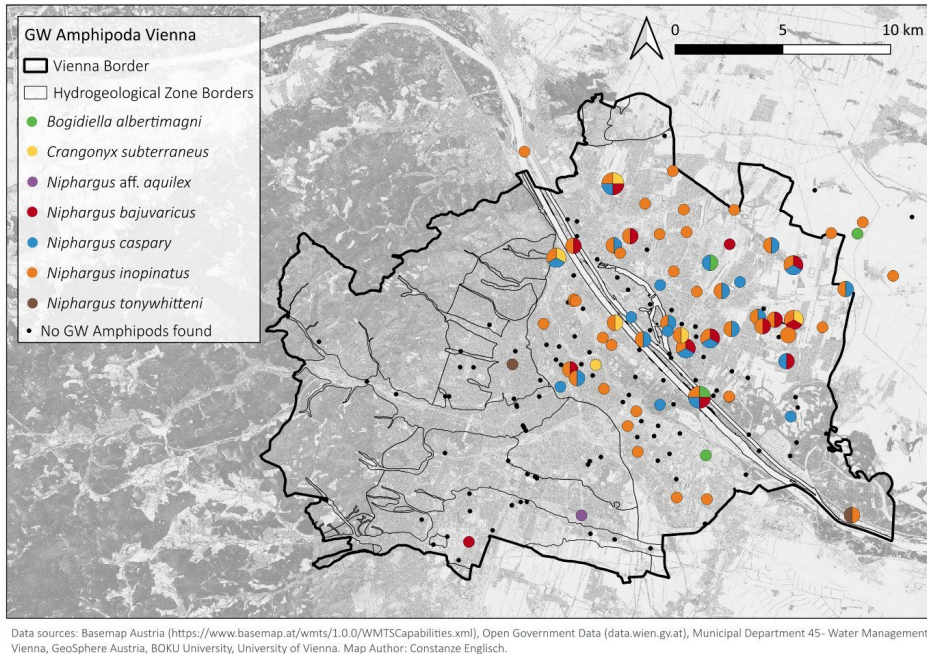


Fig. 8: Spatial distribution of amphipod species across the study area in Vienna. Each point represents a sampled site. At sites where amphipods were detected, pie charts indicate the occurrence of the different species, with colours corresponding to the respective species. Sites without amphipods are shown as black points. Fine black lines indicate the borders of the major hydrogeological zones in Vienna which are depicted in detail in Figure 1. | **Abb. 8:** Räumliche Verbreitung der Amphipodenarten im Untersuchungsgebiet. Standorte ohne Amphipodennachweis während der Studie sind als schwarze Punkte dargestellt. Dünne schwarze Linien sind Grenzen der hydrogeologischen Zonen. Siehe auch Abb. 1.

Additionally, some differences were observed with respect to the categorical variables. For geology/aquifer type, significant pairwise differences in species occurrence were identified, indicating that the respective species pairings differ in their distribution across aquifer types. Specifically, *N. aff. aquilex* differed from *N. caspary* ($p = 0.025$), *N. inopinatus* ($p = 0.009$), and “no Amphi” ($p = 0.042$). Additionally, *N. inopinatus* differed from “no Amphi” ($p = 0.002$). In this context, it is noteworthy that *N. aff. aquilex* was recorded at only a single site, with one occurrence in spring and one in autumn, and represented the only amphipod species detected within the aquifer type Other Stream Aquifer. The spatial distribution of amphipod species across the study area is illustrated in Figure 8.

With respect to the redox conditions, a single significant difference was detected, with *N. inopinatus* differing from “no Amphi” ($p = 0.002$). Across the redox gradient, the likelihood of detecting *N. inopinatus* increased from redox category 4 (highly reduced conditions) to category 1 (oxic conditions). A very similar, however non-significant trend was observed for most of the other amphipod species, whereas the probability of finding no amphipods increased from redox category 1 to 4. For surface water influence, no significant differences in amphipod species distributions were observed.

Discussion

Groundwater crustacean diversity in Vienna

Considering the multitude of stressors present in an urban area (Becher et al. 2022), the present study recorded an unexpectedly high diversity of groundwater crustaceans within the city of Vienna, with a total of 47 stygobiont/stygophile taxa identified. Figure 9 depicts a selection of species that represent the major taxonomic groups of crustaceans. Direct comparisons with other cities are limited, as only a few studies in Central European cities have previously investigated stygofauna (Buder 2019; Koch et al. 2021; Dumnicka et al. 2025a, 2025b). Most of these other studies have not analysed the urban stygofauna to species level, but rather on a coarser taxonomic level as well as with a lower spatial resolution and sampling density. However, comparison suggests that the groundwater fauna biodiversity in Vienna is exceptionally high compared to other cities, as well as to rural and more natural groundwater ecosystems of a similar size, including well accepted hotspots of subterranean biodiversity (Ferreira et al. 2007; Culver et al. 2021; Griebler et al. 2023b).

The exceptional richness observed in Vienna is likely rooted in its geological and ecological history. The city developed on a formerly dynamic floodplain shaped by the unregulated Danube River. Over long periods of time, this generated a diverse array of groundwater habitats and facilitated the diversification of groundwater fauna. Today, pronounced environmental heterogeneity, including geological variability, spatially heterogeneous hydrological conditions, and differing degrees of surface water influence, helps to explain how such high levels of diversity have been maintained. Moreover, the linkage between the city of Vienna and the Lobau wetland as part of the Danube Floodplain National Park (DFNP) is expected to facilitate faunal exchange and recolonization, supporting regional genetic exchange and adaptation. In addition, groundwater across large parts of Vienna exhibited oligotrophy, i.e. a low productivity mirrored by low amounts of organic matter and microbial biomass, and did at the same time contain sufficient amounts of dissolved oxygen, providing favourable conditions for groundwater crustaceans. Overall, the combination of historical habitat formation and present-day environmental heterogeneity appears to have enabled the persistence of an exceptionally diverse groundwater crustacean community within a densely populated urban area, with a taxon richness comparable to other groundwater biodiversity hotspots (Ferreira et al. 2007; Culver et al. 2021; Griebler et al. 2023b).

Comparing the groundwater crustacean species list compiled in this study with the species that were previously known for Vienna and adjacent regions, some species were rediscovered, some could not be found again, some have never been found in this area before, and some are even new for science. Species that have been rediscovered include *Cryptocandona kieferi danubialis*, *Mixtacandona laisi*, *M. spandli*, *Pseudocandona lobipes*, *Typhlocypris eremita* and *Kovalevskiella elisabethae* (Ostracoda - previous records compiled by Griebler et al. 2023b), *Nitocrella hirta hirta*, *Fontinalicaris fontinalis fontinalis* and *Parastenocaris* sp. (Harpacticoida - previous records by Vornatscher, 1972; Danielopol & Pospisil, 2001), *Acanthocyclops gmeineri*, *A. kieferi*, *A. rhenanus*, *A. sensitivus*, *A. venustus*, *Diacyclops cohabitatus*, *D. danielopoli*, *D. felix*, *D. languidoides goticus*, *D. languidoides languidoides*, *Eucyclops graeteri* and *Paracyclops fimbriatus* (Cyclopoida - previous records compiled by Griebler et al. 2023b),

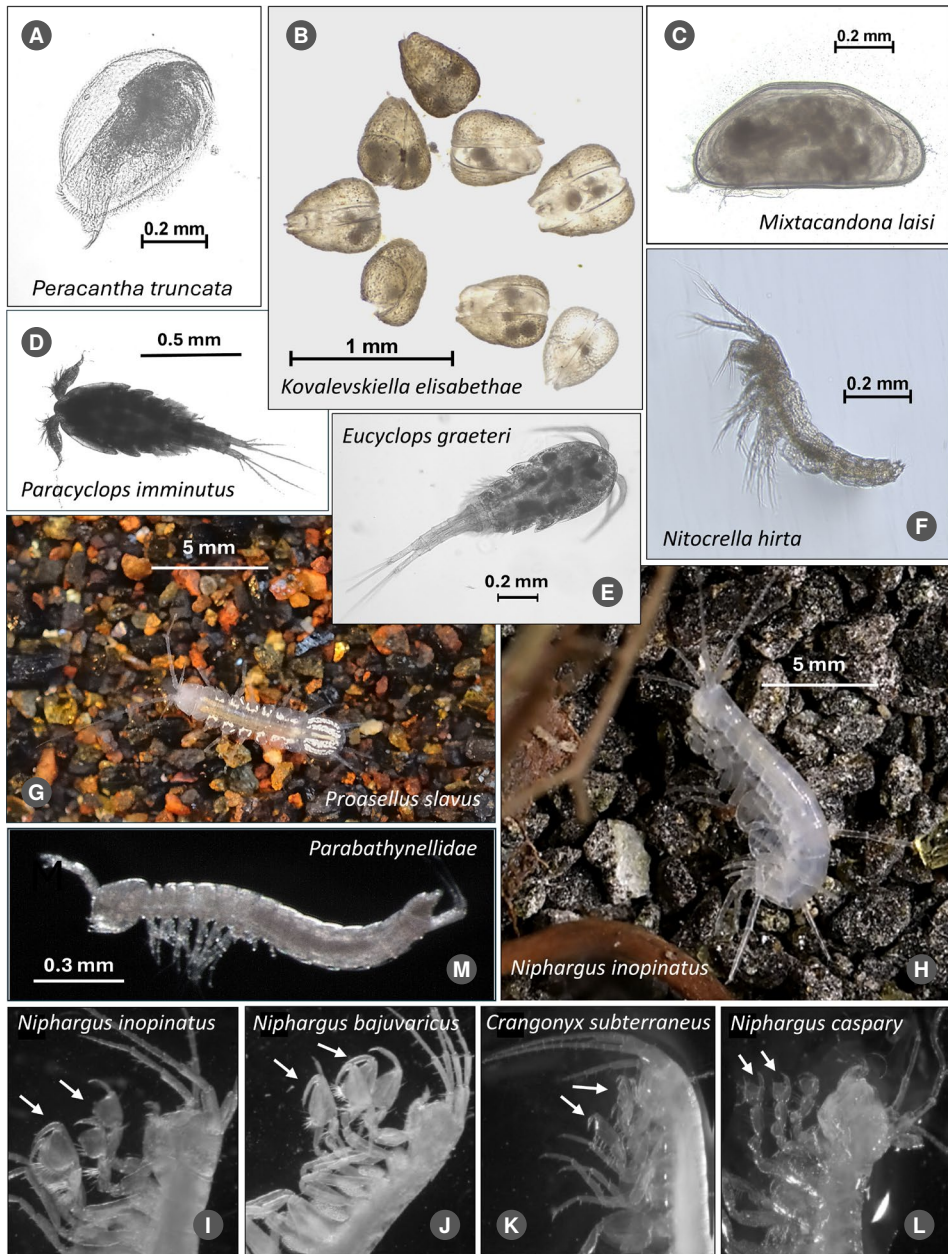


Fig. 9: The composition of pictures shows stygobiont and stygophile crustaceans from Viennese shallow groundwater habitats, representing the taxonomic groups (A) Cladocera, (B+C) Ostracoda, (D+E) Cyclopoida, (F) Harpacticoida, (G) Isopoda, (H–L) Amphipoda, and (M) Bathynellacea. The pictures I–L depict the gnathopods (white arrows) of four different stygobiont amphipod species occurring below Vienna. The gnathopods are modified first two pairs of walking legs mainly used for handling food & prey. Their shape and size help in identification of different taxa and provide evidence for feeding

behavior and food sources. © (A–F) Santiago Gaviria, (G) Günther Teichmann, (H) Kurt Kracher, (I–L) Ayac Iuan Jiménez Salvador, (M) Constanze Englisch. | **Abb. 9:** Die Bildertafel zeigt stygobionte und stygophile Crustaceen aus oberflächennahen Grundwasserlebensräumen unter Wien. Folgende taxonomische Gruppen sind vertreten: (A) Cladocera (Wasserflöhe), (B+C) Ostracoda (Muschelkrebse), (D+E) Cyclopoida (Hüpfertiere), (F) Harpacticoida (Rauenhüpfertiere), (G) Isopoda (Asseln), (H–L) Amphipoda (Flohkrebse), and (M) Bathynellacea (Brunnenkrebse). Die Bilder I–L zeigen den Kopf und die Gnathopoden (weiße Pfeile) von vier in Wien vorkommenden Grundwasserflohkrebsarten. Die Gnathopoden sind die vordersten beiden Schreitbeinpaare die zu einer Art Händen umfunktioniert sind. Die Form und Größe sind ein wichtiges Bestimmungsmerkmal und geben Auskunft über die Ernährungsweise der Tiere.

Bathynellidae gen. sp. and Parabathynellidae gen. sp. (Bathynellacea - previous records by Strouhal, 1964; Vornatscher, 1972; Danielopol, 1976; Serban, 1989;), *Bogidiella alberti-magni*, *Crangonyx subterraneus*, *Niphargus bajuvaricus*, *Niphargus caspary* and *Niphargus inopinatus* (Amphipoda - previous records compiled by Griebler et al. 2023b), and *Proasellus slavus* (Isopoda - previous records compiled by Griebler et al. 2023b). Therefore, the majority of the crustacean taxa found in this study (60 %) were known from Vienna and surrounding regions, however, with some that were last found several decades ago. A large portion (40 %) of taxa was newly discovered for the Vienna area. This underlines the necessity and relevance of high-resolution sampling efforts.

Besides the rediscovered and newly discovered taxa, some species were previously found in the Vienna area but could not be confirmed in this study. Reasons can be manifold, including local rarity or extinction. One reason can be taxonomic uncertainty, as the groundwater ecosystem in Vienna hosts several cryptic species and not all historic records may withstand a verification by means of modern methods. For example, the case of *Niphargus* aff. *aquilex* highlights taxonomic uncertainty, as historical records of *N. aquilex* in the Vienna area exist, but there is evidence that the formerly assigned and newly analysed specimens do not belong to the *N. aquilex* species complex. The phylogenetic analyses revealed that the sequences obtained in this study do not cluster with any confirmed *N. aquilex* sequences, but only with a single unresolved *N. aff. aquilex* sequence from Luxembourg (Weber et al. 2022). Given the lack of a monophyletic *N. aquilex* clade and the ongoing revision of this species complex (Weber et al. 2023, 2025), the Vienna population may represent an undescribed species or subspecies.

In the cases of several other taxa, historical records only describe a genus or species, while our current findings report corresponding species or subspecies, and *vice versa*. Historical records describe several *Proasellus* species and subspecies of *P. slavus*. Current molecular analyses, including specimen from this study (exclusively *P. slavus*) as well as data collected independently of this study, indicate a wide-spread occurrence of *P. slavus* throughout the city with less abundant occurrences of *P. strouhali* (C. Novotny pers. comm.). With respect to the main focus on amphipod assemblages in this study, the combination of morphological and molecular analyses was successfully implemented. This is reflected in the largely coherent identification (morphologically and molecularly) of seven amphipod species in Vienna, as well as new insights in the *N. aff. aquilex* case, the first detection of *Niphargus tonywhitteni* in Vienna, and the first molecular verification of *Bogidiella alberti-magni* in Vienna. Overall, the groundwater amphipod fauna of Vienna largely conforms established biogeographic

distribution patterns within Central Europe and the Danube catchment. An exception is *N. tonywhitteni*, as this species was described only quite recently from Upper and Lower Austria, Tyrol (Fišer et al. 2018), Switzerland (Alther & Altermatt 2021), and southern Bavaria (Weber 2024). The present record further extends its known distribution to the east. Molecular analyses indicate that specimens previously identified morphologically as *N. fontanus* cluster with *N. tonywhitteni*, supporting recent evidence that historical records of *N. fontanus* may represent misidentifications (Weber 2024). Consequently, the historical record of *N. fontanus* from 1972 (Vornatscher 1972) in Vienna may in fact correspond to *N. tonywhitteni*, implying that this species really has been confirmed rather than newly detected for Vienna.

Community compositions and environmental influences

Understanding the environmental factors that shape groundwater communities is essential for explaining patterns of subterranean biodiversity. We show a key influence of geology/aquifer type, dissolved oxygen (DO) concentration, and surface water influence (Tab. 2). Nevertheless, our model explained only a small fraction of the observed variation ($\approx 15\%$). The geology/aquifer type emerged as the most influential variable with respect to crustacean community composition. Different aquifer types provide distinct environmental conditions and habitat qualities that may be favourable for certain taxa, while unfavourable for others. Smaller groundwater crustaceans with particularly elongated bodies (Bathynellacea and Harpacticoida) were found more frequent in habitats with lower K_f values, despite groundwater fauna generally preferring larger pore space and higher permeability, which provides a better replenishment of oxygen and food (Hose et al. 2017; Korbel et al. 2013, 2019; Korbel & Hose 2015). In fact, crustaceans with larger body sizes (Amphipoda and Isopoda) were mostly found in gravel aquifers with high K_f values. Finer sediments may serve as refugia for stygofauna with smaller body sizes, limiting access for larger predators and competition. However, sample sizes for bathynellids and harpacticoids were relatively small, and further data is needed to confirm these patterns. The role of geological heterogeneity and sediment structure in shaping subsurface invertebrate communities is generally well established (Schmidt & Hahn 2012; Korbel and Hose 2015). However, in our study the limited explanatory power is consistent with the subsequent occurrence-based analyses, which showed no significant associations between aquifer type and total crustacean occurrences. Only a few patterns emerged but were largely restricted to specific taxonomic groups or species.

Dissolved oxygen emerged as the most consistent predictor across the statistical analyses. Higher DO levels tended to be associated with communities dominated by Amphipoda, Cyclopoida, Bathynellacea, and Isopoda, while lower DO coincided more with Ostracoda-dominated assemblages. Most crustacean groups occurred primarily under oxic conditions and were negatively associated with low oxygen and reduced conditions indicated by elevated ammonium and ferrous iron concentrations. This is also mirrored in the relationship with the redox categorical variable, as most crustacean groups, were confined to oxic environments and absent under highly reduced conditions, while moderately reducing conditions seemed to limit, but not entirely prevent, their occurrence. This suggests that DO levels ≤ 2 mg/L already begin to negatively affect crustacean occurrence, with progressively reducing conditions further aggravating this effect. Nevertheless, crustaceans were

occasionally also found at very low DO levels, pointing at short-term tolerance of hypoxic conditions, consistent with previous reports (Danielopol 1989; Malard & Hervant 1999; Mösslacher 2000). While DO concentrations below 1 or 0.5 mg/L are defined as critical (Malard & Hervant 1999; Strayer 1994; Hahn 2006), levels below 0.1 mg/L are believed to strictly limit longer survival (Strayer et al. 1997). Stygobionts can endure fluctuating DO availability through rapid recovery from anaerobic stress, allowing them to exploit a range of suboxic (< 0.3 mg/L), dysoxic (0.3–3.0 mg/L), and oxic (> 3 mg/L) habitats (Danielopol et al. 1994; Malard & Hervant 1999). This likely explains their presence across a broad range of DO availability, although they may clearly prefer well-oxygenated conditions, which is confirmed by our study and reported in other studies as well (Pospisil 1994; Pospisil et al. 1994; Malard et al. 1996b, 1997).

In accordance with the findings regarding DO and redox-sensitive variables is the positive association of total crustacean occurrences, and specifically isopods, harpacticoids and cyclopoids, with nitrate. Nitrate is microbially only turned over at hypoxic to anoxic conditions. As such presence of nitrate generally assumes the presence of dissolved oxygen. Despite being one of the most prominent groundwater pollutants (Becher et al. 2022), nitrate appears to influence groundwater crustaceans less negatively than previously assumed (Dumas & Lescher-Moutoué 2001; Galassi et al. 2009; Di Lorenzo & Galassi 2013; Di Lorenzo et al. 2021; Gerhardt 2020; Jemec-Kokalj et al. 2026). On the contrary, groundwater crustaceans regularly exhibit a strong sensitivity to ammonium (Becher et al. 2022), which is in accordance with the negative correlation between ammonium and the presence of total crustaceans, and specifically amphipods, bathynellids, cyclopoids, and isopods observed in this study. Ammonium is quite stable under reduced conditions but microbially oxidized to nitrite and nitrate upon availability of dissolved oxygen. Additionally, microbiological variables and proxies, including microbial activity (intracellular ATP), bacterial abundance (TCC), and dissolved organic carbon (DOC), showed a significant negative relationship with the presence of total crustaceans, and specifically amphipods, cyclopoids, and isopods. These variables have been proposed bioindicators of groundwater ecosystem status sensitively hinting at disturbances such as surface water influence and organic contamination (Fillinger et al. 2019), with elevated values frequently linked to oxygen depletion and reducing conditions (Kunkel et al. 2002). Moreover, higher levels of energy enhancing food availability, have been shown to promote the invasion of stygoxen and epigean species (Malard et al. 1994, 1996a; Sket 1999).

Amphipoda showed a significant preference for lower temperatures, whereas no significant effects were detected for the other groups of crustaceans. Elevated groundwater temperatures are widely recognized as a major stressor in groundwater ecosystems (Briellmann et al. 2009; Griebler et al. 2016). Urban aquifers regularly experience groundwater warming due to extensive surface sealing, geothermal installations, district heating systems, heat emission from sewage pipes and underground infrastructure (Taniguichi et al. 2005; Menberg et al. 2013; Kaminsky et al. 2025b). Exposure to temperatures outside the natural thermal range (usually 10 - 12°C in low altitude regions of Central Europe) induces physiological stress (e.g. suppresses reproduction) in groundwater invertebrates (Bannick et al. 2008; Thulin & Hahn 2008; Griebler et al. 2016). Above 14°C, groundwater crustacean biodiversity was found to significantly change in the Upper Rhine Valley (Spengler 2017). Briellmann et al. (2011) reported strong negative effects of prolonged thermal stress with *Niphargus*

inopinatus exhibiting an LT_{50} (temperature causing 50 % mortality with the test organisms) of 20.2 °C after 20 days of exposure, which is very close to the upper temperature threshold observed for amphipods in this study. Worth mentioning, the LT_{50} values were much lower with *Proasellus cavaticus* (Briellmann et al. 2011). Besides direct effects, increasing water temperatures are linked to reduced oxygen solubility while simultaneously increasing metabolic demand/rates of microbes and metazoans reducing oxygen levels further. The overall absence of crustaceans at temperatures above 22 °C is consistent with the findings by Foulquier et al. (2011), who reported an almost complete absence of groundwater fauna above this threshold.

Regarding interactions with surface water, distance to surface water affected groundwater Crustacea distribution, but effects were limited. Only Cyclopoida showed a significant preference for habitats farther from surface waters. In areas close to surface water, stronger hydrological exchange also increases the likelihood of pollutant entry from infiltrating surface water, which may reduce habitat suitability and outweigh potential benefits, such as higher food availability. With respect to the variable “surface water influenced”, only Ostracoda exhibited a significant positive association. Ostracoda also appeared to tolerate varying DO levels and microbial loads and may thus benefit from additional organic material imported. Surface water influence played only a comparatively minor role in structuring groundwater communities. Previous studies suggest that strong surface water influence can promote entry of stygophile and hyporheic species, whereas non-influenced samples tend to be dominated by stygobionts (Schmidt & Hahn, 2012); notably, in this study, the stygophile species *P. lobipes* was predominantly found in wells influenced by surface water, supporting these observations.

Several hydrochemical parameters were significantly associated with individual crustacean groups, however, it was found that these patterns likely simply reflect the geological background rather than direct physiological effects from water components. Due to the observed values being well below thresholds that were shown to negatively impact groundwater species, hydrochemical variables appeared to shape taxa distribution rather indirectly through geological and hydrogeological context, than through toxicity. The modest explanatory power of the aquifer type for several taxa further suggests that small-scale heterogeneity and groundwater mixing processes may override coarse geological classifications.

Certain parameters showed statistically significant associations with crustacean occurrence, but their ecological interpretation remains challenging. Water column height was negatively associated with occurrences of Bathynellacea, Cyclopoida, and Harpacticoida, with lower water levels corresponding to higher occurrences. Although a positive effect could be explained by larger filter sections facilitating fauna entry from different depths, the observed negative relationship remains difficult to interpret. The percentage of surface sealing had a significant but counterintuitive effect with Harpacticoida. This group unexpectedly showed higher occurrence in more strongly sealed areas, despite sealed surfaces generally reducing groundwater recharge, and contributing to groundwater warming (Tissen et al. 2019). Given the low overall occurrence of Harpacticoida in this study, this finding should be interpreted with caution and requires confirmation.

Seasonality had no significant effect on groundwater crustacean community composition, which is consistent with the findings of Korbelt & Hose (2015). While groundwater habitats are environmentally more stable than surface waters, dependent to depth they are subject to seasonal fluctuations, often with a certain delay (Steiner et al. 2024). Stygofauna species appear to be well adapted to moderate fluctuations, particularly those living in shallow aquifers. Nevertheless, the rapid pace of climate change may challenge this fragile adjustment, potentially leading to a cumulative negative effect on groundwater fauna biodiversity in the future (Englisch et al. 2024; Kaminsky et al. 2025b) – an aspect that requires further research.

Species-specific patterns among amphipods

Assessing species-specific environmental associations is challenging due to strongly uneven sample sizes between species, with several species being represented by only a few records. The most significant differences emerged from comparisons between samples with and without amphipods rather than between single amphipod species. Consistent patterns could be observed for the variables DO, ferrous iron, redox category, TCC, ATP and DOC, with amphipods generally occurring more frequently under oxic conditions with lower microbial activity/abundance as well as lower ferrous iron and DOC concentrations. Although mainly the most frequently recorded amphipod species (*Niphargus inopinatus*, *N. caspary* and *N. bajuvaricus*) reached statistical significance for most variables, similar trends were exhibited by nearly all amphipod species, suggesting broadly comparable environmental associations rather than strong niche segregation.

Interspecific differences were most notably observed in the cases of *Bogidiella albertimagni* and *Niphargus* aff. *aquilex*. *B. albertimagni* occurred at greater well depths and water column heights as well as lower microbial activity, which could indicate a higher affinity to somewhat deeper, more stable groundwater habitats. *N.* aff. *aquilex* was detected exclusively at a single site with very distinct hydrogeochemical characteristics (e.g. a unique aquifer type, elevated ATP, TCC, and DOC concentrations, moderate to high DO levels, a very short water column, shallow well depth, high surface sealing, very low hydraulic conductivity, and exceptionally high electrical conductivity). The differences in environmental associations of *N.* aff. *aquilex* could indicate a highly specialized habitat preference or distinctive tolerances of this species, but more likely reflect site-specific conditions rather than ecological specialization. Given the low number of records these patterns should be interpreted cautiously.

With respect to aquifer type, the results indicated an overall association of amphipods (especially of the most frequently found *N. inopinatus*) with high interstitial connectivity (Danube Plains), in contrast to samples without amphipods, which were more frequent in settings with low hydraulic conductivity. This underlines the importance of hydraulic connectivity and pore space for groundwater amphipods. Interestingly, *N. tonywhitteni* was the only species recorded in a Local Aquifer, whereas the Liesing Stream Aquifer was exclusively inhabited by *N. bajuvaricus*. In contrast to *N.* aff. *aquilex*, however, these species were not restricted to single sites or aquifer types. Overall, this suggests that at least the more frequently encountered amphipod species occupy similar aquifer types and do not exhibit strong species-specific segregation at this scale. Ultimately, the results suggest that common amphipod species show largely similar environmental preferences, while apparent differences involving

rarer taxa are likely influenced by the limited sample sizes. Larger datasets or meta-analysis are proposed to determine whether these patterns reflect genuine ecological differentiation or statistical artefacts. Worth mentioning in this context is the difference in morphological traits related to feeding found with commonly occurring amphipod species (Fig. 9).

Conclusion and Outlook

This study advances our understanding of groundwater crustacean fauna, particularly in urban environments such as the city of Vienna. The discovery of 47 stygobiont and stygophile crustacean taxa, which is an exceptionally high richness for an urban setting, highlights substantial knowledge gaps in the distribution and diversity of these organisms and underscores the need for continued research. Despite their ecological importance, subterranean ecosystems/species remain poorly represented in conservation frameworks. Limited knowledge on stygofauna distribution and ecological requirements, combined with the restricted accessibility of groundwater ecosystems, continues to hinder effective conservation planning. Recent initiatives aim to address these gaps. At the European level, the Biodiversa+ project “DarCo – The vertical dimension of conservation” seeks to integrate subterranean ecosystems into the EU Biodiversity Strategy for 2030, while national projects such as “Stygofauna Austriaca” and “Heat below the City” focussed on groundwater biodiversity, resilience and protection, the latter emphasizing urban aquifers in Vienna. Despite increasing attention, specifically urban groundwater ecosystems remain understudied. Ecologically, the identification of key environmental drivers is crucial for developing effective conservation strategies. Our study showed that maintaining oxygen-rich, oligotrophic conditions and avoiding excessive warming represent impactful and feasible conservation measures. Similar preferences for environmental conditions suggest that basic conservation strategies could effectively protect groundwater crustacean fauna without multiple species- or community-specific measures. However, rare taxa, including *B. albertimagni*, *N. tonywhitteni*, *C. subterraneus* and particularly *N. aff. aquilex*, require specific attention in future research to uncover their environmental demands and ecological roles. In the future, the combined application of morphological and molecular methods, as demonstrated here, offers a promising approach to resolve taxonomic uncertainties. Moreover, interdisciplinary approaches, integrating ecological, geochemical and hydrological perspectives are crucial in advancing our understanding of groundwater ecosystems and its biodiversity.

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Author contributions

CN contributed to conceptualization, data curation, analysis and visualization, interpretation and discussion of results, took lead in writing of the original draft, and assisted in reviewing and editing. CE contributed to data curation, analysis and visualization, interpretation and discussion of results, assisted in writing of the original draft, as well as in reviewing and editing, and acquired additional funding. CZ contributed to conceptualization, data analysis and visualization, interpretation and discussion of results, and assisted in reviewing and editing. FS supported in molecular analysis and assisted in reviewing and editing. AF contributed with morphological species identification and assisted in reviewing and editing. SG contributed with morphological species identification and assisted in reviewing and editing. EK contributed to data curation and analysis and assisted in reviewing and editing. CStumpp contributed to acquisition of funding, project coordination, data curation, and assisted in reviewing and editing. CSteiner contributed to data analysis and assisted in reviewing and editing. EBN contributed to data analysis and assisted in reviewing and editing. CK contributed to data analysis and assisted in reviewing and editing. CG was project leader, contributed to conceptualization, data curation, analysis and visualization, interpretation and discussion of results, guided the reviewing and editing process, and acquired the main funding.

Electronic Supplement

S1: Project “Heat below the City2. Groundwater environmental data of the city of Vienna from 2021 and 2022. | **S1:** Projekt „Hitze unter der Stadt“. Daten zur Grundwasserfauna in Wien aus 2021 und 2022.

https://www.zobodat.at/pdf/supp/Nilles_et_al_Supplement_1.xlsx

S2: Project “Heat below the City”. Groundwater fauna data of the city of Vienna from 2021 and 2022. | **S2:** Projekt „Hitze unter der Stadt“. Daten zur Grundwasserfauna in Wien aus 2021 und 2022.

https://www.zobodat.at/pdf/supp/Nilles_et_al_Supplement_2.xlsx

S3: Uncollapsed phylogenetic tree based on COI sequences from amphipod species sequenced in the HBTC project. | **S3:** Detaillierter Phylogenetischer Baum auf Basis von COI Sequenzen für ausgewählte Amphipoden aus der Projektstudie HBTC.

https://www.zobodat.at/pdf/supp/Nilles_et_al_Supplement_3.pdf

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Temporal dynamics of arthropods at “Hoher Sonnblick” (3100 m.a.s.l.)

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Biodiversity loss is driven by landscape transformation, intensive agricultural practices, and climate change. Climate change-induced temperature increases are also causing shifts in the distribution of many temperature-sensitive animal and plant species. Alpine arthropod communities are particularly sensitive to such changes, as demonstrated by observations at the summit of Hoher Sonnblick (3106 m, Hohe Tauern National Park, Salzburg). This study aimed to analyze the effects of various environmental parameters on the occurrence, abundance, and temporal dynamics of arthropods, and to evaluate the effectiveness of different sampling methods. Over a 28-day period in July and August 2023, a total of 3002 arthropod individuals representing 109 morphospecies and 13 orders were identified. Temperature, wind speed, and relative humidity significantly influenced species richness and abundance, while heavy snowfall triggered a mass emergence of *Desoria saltans* (Collembola). The different trapping methods captured distinct arthropod assemblages: pitfall traps were particularly effective for ground beetles and spiders, whereas cross-window and Malaise traps mainly sampled dipterans and lepidopterans. However, all methods were susceptible to extreme weather conditions. A combination of sampling approaches provided the most comprehensive representation of alpine invertebrate diversity. These findings highlight the role of alpine summits as refugia for endemic species and potential stepping stones for range shifts under climate change. Their protection and ecological connectivity are crucial to buffer the impacts of ongoing environmental change.

Wagner SM & Petermann JS (2026) Zeitliche Dynamik von Arthropoden am „Hohen Sonnblick“ (3100 m)

Der Verlust der Biodiversität wird durch Landschaftsveränderung, intensive Landwirtschaft und den Klimawandel vorangetrieben. Klimawandelbedingte Temperaturanstiege führen zudem zu Verschiebungen in der Verbreitung vieler temperaturempfindlicher Tier- und Pflanzenarten. Besonders sensibel reagieren alpine Arthropodengemeinschaften, wie sie am Gipfel des Hohen Sonnblicks (3106 m, Nationalpark Hohe Tauern, Salzburg) untersucht wurden. Ziel dieser Studie war es, die Effekte verschiedener Umweltparameter auf Vorkommen, Häufigkeit und zeitliche Dynamik von Arthropoden zu analysieren sowie die Effektivität unterschiedlicher Erfassungsmethoden zu vergleichen. Über einen Zeitraum von 28 Tagen im Juli und August 2023 wurden 3002 Arthropodenindividuen aus 109 Morphospezies und 13 Ordnungen gesammelt. Temperatur, Windgeschwindigkeit und Luftfeuchtigkeit beeinflussten Artenreichtum und Abundanz signifikant; starker Schneefall führte zu einem Massenaufreten von *Desoria saltans* (Collembola). Die verschiedenen Fangmethoden erfassten unterschiedliche Artengruppen: Barberfallen waren besonders geeignet für Laufkäfer und Spinnen, während Kreuzfenster- und Malaisefälle v. a. Dipteren und Falter erfassten. Alle Methoden erwiesen sich jedoch als wetteranfällig. Eine methodische Kombination bietet das vollständigste Bild der alpinen Wirbellosenvielfalt. Die Ergebnisse unterstreichen die Rolle alpiner Gipfel als Refugien von Endemiten und als potenzielle Trittsteine für Arten im Klimawandel. Ihr Schutz und die ökologische Vernetzung sind entscheidend, um klimabedingte Veränderungen abzufedern.

Keywords: arthropod communities, biodiversity, community ecology, high alpine areas, National Park Hohe Tauern, Sonnblick Observatory.

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Introduction

Over the past century, rapid land use changes have led to a collapse in arthropod populations (Hallmann et al. 2017; Carson 2021), posing a significant risk to ecosystem functions (Ruczyński et al. 2020) and services. Particularly vulnerable are isolated areas such as mountain tops, which harbor numerous endemic species (Nagy 2003; Mertz 2017). These regions are limited in space and thus more susceptible to environmental changes caused by habitat fragmentation, the extensive use of pesticides, and climate change (Dietz & Kiefer 2024; Settele 2020).

The Alpine Arc has experienced an air temperature rise at a rate twice as high as the global average since the late 20th century (Streitberger et al. 2016; Jandl et al. 2024). The predicted temperature shift comes with consequences concerning distributions of species along the elevational gradient (Streitberger et al. 2016). These changes may increase competition pressures on endemics and other species with narrow ecological amplitudes (Hofer 2009; Singer 2016), possibly leading to their local extinction. Within central Europe, the highest number of endemic species can be found in Austria (Rabitsch & Essl 2009).

Alpine habitats are characterized by high wind velocities, rapid temperature drops, strong UV-radiation, and long periods where the soil is covered with snow or ice (Lee & Denlinger 1991; Mertz 2017). Over time, the central Alps produced a diverse ecosystem which is adapted to its harsh and unpredictable climate (Ernakovich et al. 2014). With climate change, thermosensitive species may migrate further upwards along longitudinal and elevational gradients (Kerner et al. 2023) to escape alternating environmental conditions. These changes may pose additional threats to high alpine species (Rabitsch & Essl 2009). Some species, especially Lepidopterans, migrate (Mazzucco 1975) which leads to swarming events possibly driven by shifting climate.

This project investigated arthropod diversity in a high alpine ecosystem to test how environmental factors influence arthropod diversity and community composition. It also compared different sampling methods to determine their effectiveness in harsh conditions and explored changes over time, including possible swarming events.

Our hypotheses were that 1) apparent arthropod abundance and richness change with environmental parameters (wind speed, wind direction, air temperature, soil temperature, relative air humidity, and weather) and across time, for example due to migratory or swarming events, and that 2) composition of trapped arthropods varies between trap systems based on the selectivity of each method.

Methods

Study area

The field work was conducted at the mountain top of “Hoher Sonnblick” in Rauris (province of Salzburg) at the Sonnblick Observatory (47.054039 North, 12.957729 East, Fig. 1) at an elevation of 3106 m.a.s.l. The observatory is situated within the National Park Hohe Tauern, Central Europe’s largest contiguous national park (Stüber 1989; Hofer 2009) and supports



Fig. 1: Study location. **A)** Province of Salzburg with the Hohe Tauern National Park highlighted in green. The black arrow indicates the location of the Sonnblick Observatory at the border between the provinces of Salzburg and Carinthia. **B)** Sonnblick Observatory at the top of “Hoher Sonnblick” on the right, with the adjacent Zittelhaus alpine hut on its left side. © Sarah M. Wagner | **Abb. 1:** Untersuchungsgebiet. **A)** Bundesland Salzburg mit dem Nationalpark Hohe Tauern (grün hervorgehoben). Der schwarze Pfeil markiert den Standort des Sonnblick-Observatoriums an der Grenze zwischen Salzburg und Kärnten. **B)** Das Sonnblick-Observatorium befindet sich rechts im Bild auf dem Gipfel des Hohen Sonnblicks, links davon das angrenzende Zittelhaus. © Sarah M. Wagner

meteorological and ecological research (Ludewig et al. 2023). Adjacent to the station, there is a managed alpine hut which is operated during summer. The traps were either setup at the southern slope beneath the building complex or at the measuring terrace of the observatory. The study was executed for four consecutive weeks from 17th July to 14th August 2023.

Field data collection

Five different trap types were tested: snowfield traps, pitfall traps, cross-window traps, malaise traps and camera traps. For the snowfield traps, five areas of one square meter (Heiniger 1989) were flagged with a marker at each corner in the permanent snowfield on the southern slope (one to 50 meters apart). Samples were collected every 12 hours (morning and afternoon) where all visually detectable arthropods were collected from the snow surface with tweezers. The captured animals were stored in 70 % alcohol in Eppendorf tubes until further determination. Relocation of the transects was necessary during the sampling period due to fluctuations in snow cover. Fresh snowfall obscured snowfield traps located at glacier margins, where snow is typically retained year-round. To ensure that only newly deposited individuals were recorded, sampling was restricted to specimens present on the snow surface, and therefore only days without fresh snow were analysed.

Five pitfall traps were set up in snow-free areas with scarce vegetation to collect ground-dwelling insects (Heiniger 1989). The glass containers were buried in the ground and filled with 1–2 cm of 70%-Ethanol. A protective aluminium roof was used as a rain shield. Each trap was sampled daily, and the arthropods were stored in ethanol until further examination.

One cross-window trap was set up at the measuring terrace of the Sonnblick Observatory to intercept insects mid-flight. During the day (12 hours) it was equipped with a plastic container with ethanol as a collecting liquid for flying insects to drop into. In case of heavy rainfalls, the container was replaced with a net to avoid spill-over. These samples were stored for species determination at the lab in Salzburg. At night (12 hours) there was a light-source of different wave lengths (UV, green, blue) attached to attract nocturnal insects (Sheikh et al. 2016). For this setup the insects were guided through the funnel and into a net (instead of ethanol) to avoid wing scale loss and therefore enable identification of the moths which were expected during the night. Every morning, the moths were counted, identified with the ObsIdentify Application (Observation International 2023) and released.

One malaise trap (Fig. 2) was set up for catching flying insects and emptied daily (24-hour-intervals). The collecting vessel was filled with ≥ 96 %-Ethanol and pointed southwards (Szymank et al. 2018) following the intrinsic need of insects of flying towards the sun.

Camera traps were used to quantify insect abundance via an analysis of nighttime pictures of the sky. A RICOH WG-6 Camera (Fig. 3) was set up at the measuring terrace of the Sonnblick Observatory following the script of Ruczyński et al. (2020). Each night, whenever possible according to the weather forecast, from about 9.30 pm (sunset) to 5.30 am (sunrise), five-minute-interval flash photography was used to record nocturnal flying insects in the night sky by counting individuals depicted as reflecting ellipses in the pictures. The vertically orientated camera was set to PF-focus and locking the ISO-value to 1600.



Fig. 2: Setup of malaise trap on the southern slope located below the Sonnblick Observatory. © Sarah M. Wagner | **Abb. 2:** Aufbau der Malaise Falle am Südhang unterhalb des Sonnblick-Observatoriums. © Sarah M. Wagner

Fig. 3: Setup of camera traps on the measuring terrace of the Sonnblick Observatory pointing straight up into the night sky. The camera lenses often froze overnight due to low temperatures and high humidity. © Sarah M. Wagner | **Abb. 3:** Kamerafalle auf der Messterrasse des Sonnblick-Observatoriums mit senkrechter Ausrichtung in den Nachthimmel. Aufgrund niedriger Temperaturen und hoher Luftfeuchtigkeit froren die Kameralinse nachts häufig. © Sarah M. Wagner

Environmental parameters (air temperature, relative humidity, wind speed, etc.) were measured in 30-minute-time-intervals by the Sonnblick Observatory and are publicly available via the Sonnblick Observatory Database (<https://data.sonnblick.net/>). The daily mean of each separate sampling period (24 h-intervals for comparability between trap types) for continuous parameters (air temperature, humidity, and wind speed) was calculated. Northness and westness was calculated from wind direction given in degrees (cardinal direction) and treated the same way as the continuous parameters. Additionally, three portable TFA analogue outdoor thermometers were placed at selected traps to measure soil temperature twice a day. However, heavy snowfall events occasionally buried the thermometers beneath the snow, thus, the thermometers could not be read (missing values).

Arthropod identification

All samples were determined to at least morphospecies level using a stereomicroscope at the laboratory of the University of Salzburg with 40x magnification and the following literature: Mandl & Schönmann 1978; Schedl 1980; Böhme et al. 1983; Mertz 2008; Müller-Motzfeld 2012; Lompe 2017; Schaefer 2018; Ko et al. 2018; Müller & Bährmann 2022.

Statistical analysis

Statistical analyses were conducted in R (R Core Team 2022, v3.8.2). Some sampling days were excluded because samples could not be collected due to adverse weather conditions (e.g., thunderstorms, extreme events). Abundance and (morpho)species richness were used as response variables, with air temperature, date (Julian days), relative humidity, weather categories (sunny, few clouds, cloudy, rainy, snowy, stormy), wind direction, wind speed, and, for the cross-window trap, lunar phase (new moon, half-moon, full moon) as explanatory variables. Given the non-normality, heteroscedasticity, and overdispersion of the data, generalized linear models (GLMs) with quasi-Poisson error distribution and a log link function were applied. In addition to an overall model testing for date, daytime, trap type, and the two-way-interaction of Julian day and trap type, separate GLMs were fitted for each trap type to test for the effect of environmental parameters on both diversity parameters. Due to the small sample size and the non-independence due to the repeated sampling, results must be interpreted with caution. The map was created in QGIS (QGIS Development Team 2024, *LTR version 3.40.8*).

Results

During the sampling period of 28 consecutive days a total of 3002 individuals of 109 arthropod morphospecies (Table S2) were collected by 13 traps of five trap types. The samples ranged from 0 to 468 individuals and from 0 to 24 morphospecies. Collectively, 13 orders within three classes were found. Overall, 50 morphospecies were represented by a single individual.

Environmental effects on abundance and morphospecies richness

Starting off with a record high in temperature, the second and third week of the sampling towards the end of July 2023 were marked by snow fall at the summit. A minimum of -5.4°C

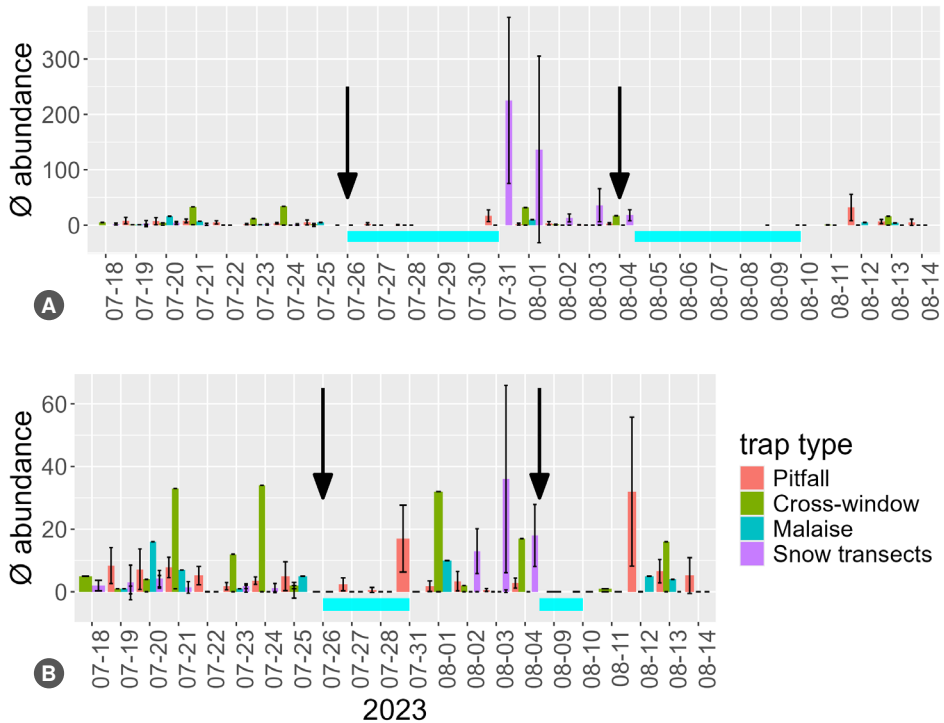


Fig. 4: Mean abundance per day and trap type with standard error for each method from 17th July until 14th August 2023: **A)** with complete data set, in **B)** the very abundant *Desoria saltans* (Collembola) were removed and missing data (days) excluded. Each method is depicted in a different colour (5 pitfall traps = red, 1 cross-window trap = green, 1 malaise trap = blue, 5 snowfield traps = purple). Two massive snowfall events on July 26th and August 4th (black arrows) were recorded, the ice blue bar beneath the x-axis highlights the period during which the soil remained widely snow-covered. | **Abb. 4:** Mittlere Häufigkeit pro Tag und Fallentyp mit Standardfehler für jede Methode vom 17. Juli bis 14. August 2023: **A)** mit vollständigem Datensatz, in **B)** wurden die sehr häufigen *Desoria saltans*-Individuen (Collembolen) entfernt und fehlende Daten (Tage) ausgeschlossen. Jede Methode ist in einer anderen Farbe dargestellt (5 Barberfallen = rot, 1 Kreuzfensterfalle = grün, 1 Malaisefalle = blau, 5 Schneefeldfallen = violett). Zwei massive Schneefallereignisse am 26. Juli und 4. August (schwarze Pfeile) wurden aufgezeichnet, der eisblaue Balken unter der x-Achse markiert den Zeitraum, in dem der Boden weitgehend schneebedeckt blieb.

and an increase in relative humidity was observed. Despite rising temperature towards the end of sampling period, the ground even at the exposed summit was still covered in snow.

The trap type had a highly significant effect on mean abundance where the highest number was found in pitfall traps (Table S2). High abundances were observable on July 31st and August 1st. Here, snowfield traps were predominantly populated by one species: the glacier flea *Desoria saltans* (Collembola) when snow melt events after heavy snowfall led to aggregation on the snow-surfaces (Fig. 4, first black arrow) on July 26th.

Tab. 1: Results of the overview model to depict differences between trap types: Results of the generalized linear model testing the effect of the environmental variables on arthropod abundance or arthropod species richness of the complete Sonnblick data set with Df = Denominator degrees of freedom and Df Resid. = Degrees of freedom of Residuals. Significant effects are indicated by bold font. | **Tab. 1:** Ergebnisse des Übersichtsmodells zur Darstellung von Unterschieden zwischen Fallentypen: Ergebnisse des generalisierten linearen Modells zur Prüfung des Einflusses von Umweltvariablen auf die Arthropodenpopulation bzw. den Arthropodenartenreichtum des gesamten Sonnblick-Datensatzes mit Df = Freiheitsgrade des Nenners und Df Resid. = Freiheitsgrade der Residuen. Signifikante Effekte sind durch Fettdruck gekennzeichnet.

Variable	Df	Abundance			Species Richness		
		Df Resid.	χ^2	P-value	Df Resid.	χ^2	P-value
Julian day	1	87	5.98	0.686	87	11.47	0.005
Trap type	3	84	609.42	0.001	84	256.33	<0.001
Daytime	1	83	1.24	0.854	83	0.22	0.788
Julian day: Trap type	3	80	135.53	0.295	80	23.826	0.005

For species richness (Table 1) the effects of Julian day, and trap type, as well as the two-way-interaction between trap type and Julian day were significant. At the beginning and towards the end of our study period the highest number of morphospecies could be collected, especially the pitfall traps and malaise trap collected the most species at the start. When excluding the outliers on the snowfield traps, a few fluctuations were visible in the nightly setup of the cross-window traps where moth occurrences peaked occasionally.

In the separate GLMs per trap type we found significant positive effects of sunny weather and soil temperature, as well as negative effects of wind speed on mean abundance (Table S1) for the pitfall traps. There was a significant positive effect of soil temperature on species richness. For the malaise trap system significant positive effects of air temperature on mean abundance could be observed. Furthermore, significant effects of air temperature and relative humidity, on species richness were observed. A significant positive effect of relative humidity on mean arthropod abundance for the cross-window traps was shown. There were also significant positive effects of date, air temperature, and lunar phase on species richness: during full moon we measured a peak in nocturnal lepidopteran captures. When testing the snowfield trap system, a significant effect of date, relative humidity, and wind direction (northness) on mean arthropod abundance could be detected. The effect of date was positive and significant on species richness for this collection method.

Community composition and method comparison

The arthropod community at the summit of Hoher Sonnblick was dominated by *Desoria saltans* (Isotomidae, Collembola) which was found at the snow patches on the slope beneath the observatory (Table S2). Nocturnal Lepidoptera (family Geometridae and Noctuidae; total 152 individuals) were frequently collected as well, though exclusively via the cross-window traps and capture rates were limited by low temperatures. Another frequent order were the dipterans (15 families) which were present in all traps. Pitfall traps captured a variety of insect orders such as other Collembola and Coleoptera. Here, the

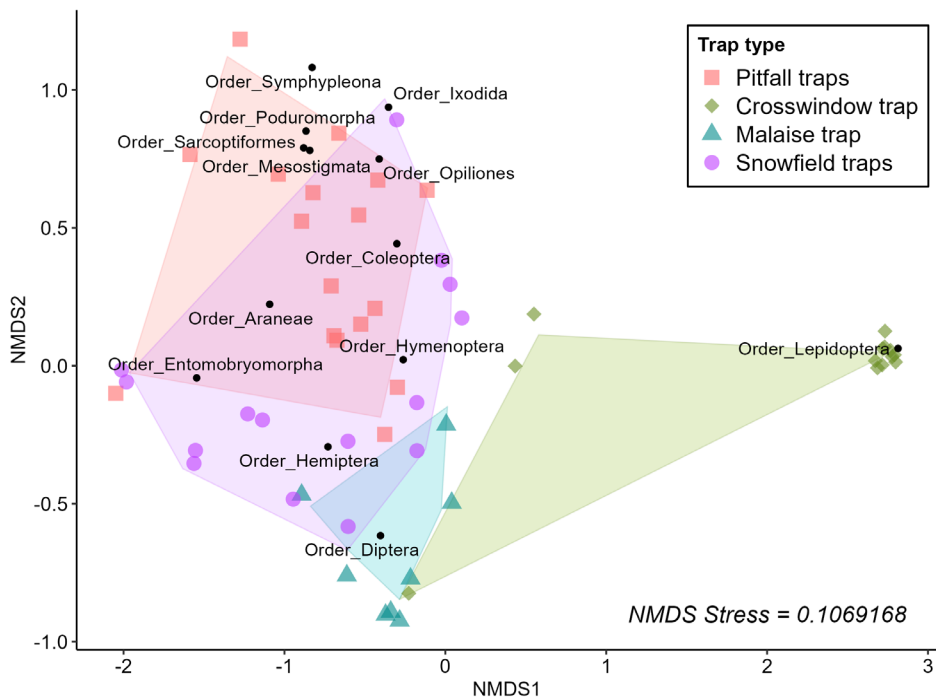


Fig. 5: Non-metric Multidimensional Scaling of the summit community on order level between the four different traps using the Bray-Curtis dissimilarity index. The symbols represent the insect order communities per trap type and sampling point (light orange squares = pitfall trap $n = 17$, purple circles = snowfield traps $n = 15$, turquoise triangle = malaise trap $n = 8$, and green diamond = cross-window traps $n = 13$). Differences in community composition are shown via distance between encircled areas. | **Abb. 5:** Nicht-metrische multidimensionale Skalierung der Gipfelgemeinschaft auf Ordnungsebene zwischen den vier verschiedenen Fallen mithilfe des Bray-Curtis-Dissimilaritätsindex. Die Symbole repräsentieren die Insektenordnungsgemeinschaften pro Fallentyp und Probenahmepunkt (hellorange Quadrate = Barberfallen $n = 17$, violette Kreise = Schneefeldfallen $n = 15$, türkisfarbene Dreiecke = Malaisefallen $n = 8$ und grüne Raute = Kreuzfensterfallen $n = 13$). Unterschiede in der Gemeinschaftszusammensetzung werden durch den Abstand zwischen den umrahmten Bereichen dargestellt.

alpine endemic *Orenoebria atrata* (Carabidae) was predominant. From the snowfield traps many bark beetles (Scolytidae) were gathered. The order Hymenoptera was the fourth most common order, represented by seven different families. In this study, mites were sometimes found still attached to their carabid hosts. Arachnids were found sparsely, yet two alpine specialists should be emphasized: *Erigone tirolensis* (Linyphiidae) and *Mitopus glacialis* (Phalangidae).

Due to limited replicates and low sample sizes, arthropod community composition was analyzed at the order level. The effect of trap type (Fig. 5; $F_{3,35} = 6.1349$, $P < 0.001$) on community composition was highly significant. Different arthropod groups were collected by different trap types. Pitfall traps sampled a variety of orders, however, mostly

ground-dwelling or pollinating arthropods. Malaise trap collected mostly dipterans. The cross-window system was most successful with moths. Snowfield traps were biased for glacier fleas (*Desoria saltans*, Collembola), but also a variety of arthropods were gathered.

Each system met limitations concerning extreme weather events and was not fully functional during all times. For instance, thunderstorms reduced the sampling days for the camera traps to eleven out of 28 days. Furthermore, only six out of these eleven offered reliable pictures without fog. Even after manual calibration before field work, the accurate interpretation of the results proved difficult with deterioration caused by rain, fog, or frost. Due to the unconvincing results, the camera method was excluded from further analysis. Other methods like the pitfall traps could not be sampled during fresh snow fall events, as they were covered with snow and therefore inaccessible.

Discussion

Our findings demonstrate that all measured environmental variables affected arthropod morphospecies richness and abundance in some way. July is generally characterized by relatively stable environmental conditions at „Hoher Sonnblick“, however, during the sampling period of 2023 a bad weather period befell Central Europe. Environmental parameters significantly influenced arthropod catches: soil temperature and wind speed affected the composition of species collected by pitfall traps; humidity increased abundance of arthropods in cross-window traps; and air temperature influenced species richness in the collections. Humidity was a key driver for *D. saltans* abundance on glacial snowfields. Similar patterns were observed in other studies (Knop et al. 2023; Sandeep et al. 2023).

Snowfield traps primarily yielded small and surface-adapted species like *Desoria saltans* and Linyphiid spiders, including *Erigone tirolensis*, or wind-dispersed insects like Scolytidae. *D. saltans* exhibited swarming behaviour after snowfall periods. Therefore, a substantial short-term increase—up to tenfold—of observable individuals could be sampled on two sampling days via snowfield traps analysis. Such mass occurrences of Collembola, including *Ceratophysella sigillata*, *Hypogastrura socialis*, and *Isotoma hiemalis*, are well-documented (Christian & Meyer 1997) and typically occur in late spring, coinciding with hatching and molting events. Molting of *D. saltans* was observed during this period in our study as well. However, as earlier studies suggest that the abundant occurrence of Collembola (Agustí et al. 2003; Somme 1989; Singer 2016) may be associated with snowmelt and surface conditions (Heiniger 1989), hence resulting in an aggregation of *Desoria saltans* on the snow surface (Kopeski 1988).

Similar fluctuations, albeit less extreme, were recorded in other methods. As cross-window traps varied in function – ethanol-based by day, UV-attractant by night – the net setup may have allowed escape. Migratory events of lepidopterans could not be confirmed; however, the moth *Autographa gamma* was frequently caught in the cross-window trap, especially during full moon nights. These observations are consistent with previous findings that lunar phase influences nocturnal insect activity (Nowinszky & Puskás 2017), though usually highest number of caught individuals would be expected during new moon or periods of fog when UV sources increase likelihood of captures, and light source type was singled out

in earlier studies as a main driver for lepidopteran catches (Nowinszky & Puskás 2017; Baker & Sadovy 1978). Migratory events for Gamma moths (Hofer 2009) and other insects (Ruczyński et al. 2020) have been observed at mountain passages in adjacent valleys in late summer (Mazzucco 1975). Some insectivorous predators have specialised on these mass occurrences (Ruczyński et al. 2020).

In our study, primarily Coleoptera, Collembola, Diptera, and Arachnida were found, including the flightless Carabid *Oreonebria atrata*, and the glacier harvestman *Mitopus glacialis*. These endemic species were commonly found in other studies as well (Rabitsch & Essl 2009; Komposch & Gruber 2004). Covers likely increased efficiency by shielding from precipitation, however, Litavský & Prokop (2024) discussed the possibility of reduced accessibility. Malaise traps remained functional under alpine extremes and sampled Diptera, Hymenoptera, and occasional Entomobryomorpha (Collembola) during snowmelt, even though, the entry could have been blocked by snow during extreme weather events. Abundance was indeed lower during snow fall events, likely also caused by effects of the adverse conditions on insect movement. All trap types exhibited specific advantages and limitations, often influenced by environmental conditions. Camera traps, though potentially effective, are constrained by humidity. Snowfield traps proved vulnerable to being completely covered, while pitfall traps could serve as a more robust alternative for collecting Collembola under unstable environmental conditions. For cross-window traps, increasing trap numbers may enhance moth sampling. The combined use of multiple trap types enabled broader arthropod sampling. Extending sampling durations and increasing replicate numbers would improve the basis for this high-altitude site and for statistical reliability.

Future improvements could include more detailed vegetation surveys in order to link arthropod communities to vegetation properties and plant species. A comparative study along altitudinal gradients would be essential to understand shifts of alpine arthropod communities with climate change and possibly predict future communities at „Hoher Sonnblick“. Less invasive methods, such as environmental DNA analysis via flower washing could reduce biomass removal and its ecological impacts. Arthropod lifecycle dynamics are significantly influenced by environmental parameters, with temperature identified as the primary driver of abundance. In the mountainous regions containing ice-free sanctuaries specialists evolved following orographic isolation (GLORIA programme 2024), which decreases chances of recolonization (Wittig & Niekisch 2014). Alpine species have been affected by the rapid increase in temperature and therefore must adapt or might become extinct soon. However, due to many technical and methodological challenges, alpine habitats are understudied. Studying alpine ecosystems is critical for informing responses to climate-driven ecological changes, which is why now is the best time to study this special ecosystem.

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pyrasti-individuals), as well as Tobias Seifert (Coleoptera) and Johannes R. Schall (Arachnids) of Paris-Lodron-University Salzburg. We sincerely appreciate all valuable comments and suggestions by the reviewers, which helped to improve the quality of the manuscript.

Electronic Supplement

Tab. S1: Results of the generalized linear model testing the effect of the environmental variables on arthropod abundance or arthropod morphospecies richness for each trap type separately. | **Tab. S1:** Ergebnisse des generalisierten linearen Modells für jeden Fallentyp.

Tab. S2: Summary of arthropod abundances and morphospecies richness per trap type | **Tab. S2:** Zusammenfassung der mit unterschiedlichen methodischen Ansätzen gesammelten Arthropoden.

Tab. S3: List of collected individuals – determined to at least Genera level and if possible, the species was identified. | **Tab. S3:** Liste der gesammelten Individuen mit Bestimmung auf Gattungsniveau, falls möglich wurde bis auf Artniveau bestimmt.

https://www.zobodat.at/pdf/supp/Wagner_Petermann_Supplement.pdf

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A structurally rich natural garden supports an exceptionally high diversity of wild bees

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Natural gardens with a high diversity of native plants, heterogeneous habitats and the absence of pesticides can serve as refuges and important secondary habitats for numerous animal species. However, little is known about the diversity of wild bees, the most important pollinators worldwide, in such natural gardens, and even less is known about the wild bee fauna of natural gardens where measures to specifically support bees have been implemented. Here, the wild bee fauna of a highly structured private natural garden in Austria of about 3700 m², which is managed to specifically promote wild bees, was investigated. In seven investigation days in 2024 and sporadic investigations from 2021 to 2023, a total of 178 wild bee species have been recorded. Among them, there were many rare, endangered and highly specialised species. A comparison with the bee fauna of botanical gardens revealed that the studied natural garden contains a remarkably high diversity of bees on a relatively small area. Overall, our data show that highly structured private natural gardens with a diverse native flora have a strong potential in supporting and promoting a high diversity of bees.

Hackl J, Dötterl S (2026) Ein strukturreicher Naturgarten mit außergewöhnlich hoher Vielfalt an Wildbienen

Durch die Förderung heimischer Pflanzenarten, die Schaffung einer hohen Habitat-Heterogenität und den Verzicht auf Pestizide können Naturgärten als Refugien und sekundäre Lebensräume für zahlreiche Arten dienen. Über die Diversität von Wildbienen, welche weltweit die wichtigsten Bestäuber darstellen, ist in solchen Naturgärten allerdings wenig bekannt. Noch geringer ist der Kenntnisstand über die Bienenfauna von Naturgärten, in denen gezielt Maßnahmen zur Förderung von Wildbienen durchgeführt wurden. In dieser Studie wurde die Wildbienenfauna eines reich und kleinräumig strukturierten, privaten, 3700 m² großen Naturgartens in Österreich untersucht, dessen Gestaltung und Management auf die Förderung von Wildbienen abzielt. An sieben Begehungstagen im Jahr 2024 und sporadischen Begehungen in den Jahren 2021 bis 2023 konnten insgesamt 178 Wildbienenarten nachgewiesen werden. Unter diesen befanden sich zahlreiche seltene, gefährdete sowie hoch spezialisierte Arten. Ein Vergleich mit den Bienenfaunen verschiedener botanischer Gärten ergab, dass der untersuchte Naturgarten auf einer verhältnismäßig kleinen Fläche eine bemerkenswert hohe Vielfalt an Wildbienen aufweist. Daraus schließen wir, dass reich und kleinräumig strukturierte Naturgärten, die eine hohe Vielfalt an heimischen Pflanzenarten aufweisen, ein großes Potenzial zur Förderung einer hohen Wildbienen Vielfalt besitzen.

Keywords: Anthophila, wild bees, natural garden, native plants, Austria, pollinator conservation, habitat heterogeneity.

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Introduction

Domestic gardens, that often make up a large proportion of a country's total area (e.g. in Sheffield, UK, approximately 23 % of the urban land area; Gaston et al. 2005), can serve as refuges and important secondary habitats for many species as natural habitats continue to be lost, degraded and fragmented by, e.g., intensive agriculture, as well as increased impervious surfaces and urban structures (Goddard et al. 2009; Braschler et al. 2021). Gardens can further serve as important stepping-stones (Lynch 2019), especially when there are networks of gardens available that improve habitat connectivity (Goddard et al. 2009; Lynch 2019). However, the potential of gardens to support and work as refuges for wildlife, including rare and endangered species, strongly depends on how a garden is managed and structured (Lynch 2019). Natural gardens can serve as an ideal habitat for many native species when native plants are promoted, a high habitat heterogeneity is created, and no pesticides or other chemicals are used (Witt 2018). Among the organisms supported in such gardens are bees (e.g. Zurbuchen & Müller 2012; Rahimi et al. 2022; Bell et al. 2023), which are the most important pollinators (Michener 2007). Worldwide, approximately 20000 different bee species do exist (Michener 2007), while in Austria, where the study site was located, the number of documented species is about 700 (Wiesbauer 2023). Bees frequently visit flowers as they are dependent on their rewards, mostly pollen and nectar, both for their own nourishment and the nourishment of their larvae (Wiesbauer 2023). Concerning the collection of pollen as food for their larvae, some species, termed as oligoleges, are specialised on species of a plant genus or plant family, whereas others, the polyleges, have a more generalized host plant spectrum (Westrich 2019). Overall, bees show a high variety of different nesting behaviours (Zurbuchen & Müller 2012). For example, for constructing their nests, many bees are specialised on specific nesting sites (e.g., existing cavities in dead wood, sparsely vegetated ground patches, pithy stems, rotten wood or empty snail shells) (Zurbuchen & Müller 2012). In order to exist at a specific site, bees do need both their specific nesting sites and their host plants in close proximity, typically within a range of 200 to 300 m (Zurbuchen & Müller 2012). As in natural gardens a high diversity of different native plant species and potential nesting sites can be created within a short distance, they should serve as ideal habitats for wild bees. In contrast to bee species-rich botanical gardens (e.g. Schanz et al. 2023), however, very few investigations exist on the bee fauna of natural gardens. Bisschop and Sedivy (2024) surveyed the wild bee fauna of a natural garden (1150 m²) in Switzerland (Regensdorf) over the course of three vegetation periods and recorded 98 bee species. Westrich (1997) recorded within five years 115 bee species in a 320 m² private garden in Germany. Zettel et al. (2018) surveyed the wild bee fauna of a natural garden in Vienna and adjacent experimental agricultural plots (covering a total area of 17000 m²) in 2013, 2017, and 2018 and recorded 134 bee species.

The aim of this study was to record the wild bee fauna of a highly structured private natural garden in Upper Austria, which is managed specifically to promote wild bees. Based on literature data, the nesting and flower visiting behaviour of recorded bees, as well as their sociality and Red List status, were analysed. We compared the recorded bee fauna to other faunistic studies available for Upper Austria. Specifically, we asked, i) How many and which bee species do occur in the garden, ii) Are only generalist and non-endangered species or also specialist and endangered species among the bees recorded, and iii) How do species number and composition of the natural garden compare to other studies performed in Upper Austria?

Material and Methods

Study area

The study was conducted in a private natural garden in Haslach in Upper Austria, around 35 km north of Linz. The garden is next to a residential area, measures about 3700 m² in size and is approximately 530 m above sea level. It is adjacent to agricultural and industrial areas. The surrounding grasslands and forests (mainly monocultures of spruce) are predominantly managed intensively. For example, most of the surrounding meadows are drained, highly fertilized and mown at least three times a year. The garden is located about 3 km away from the European Green Belt, which in this region runs along the Austria-Czech border (Gaudry et al. 2014).

The majority of the structures available in the garden, except for some hedges, trees and ponds, for example, have been created in the course of the last 10 years. The garden mainly consists of hedges, single trees and shrubs, ponds or small brooks, dry areas, drystone walls, fallow areas, meadows, fringe vegetation areas and vegetable gardens (Figure 1). The dry areas contain, among others, stone piles, standing and lying dead wood, vertically placed empty and pithy stems, areas and small hills out of sand or a mixture of sand and soil, and harbour a ruderal and pioneer vegetation. In the fallow areas, the soil gets turned over in

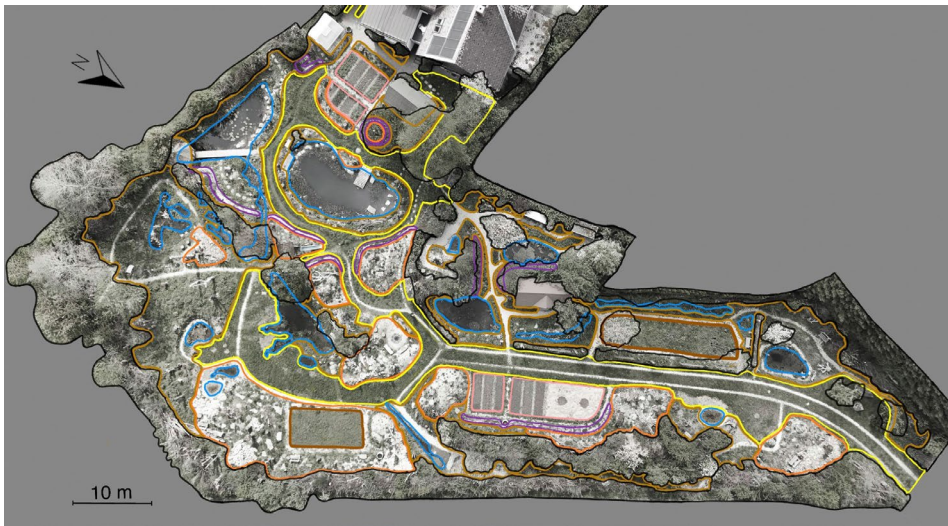


Fig. 1: Map of the studied garden. Hedges and other trees or shrubs are framed in **black**, ponds or small brooks in **blue**, dry areas (characterized e.g. by items such as stone piles, standing and lying dead wood, sandy hills and a ruderal or pioneer vegetation) in **orange**, drystone walls in **purple**, fallow areas in **brown**, and meadows in **yellow**. Fringe vegetation areas are indicated in **ochre** and vegetable gardens in **pink**. | **Abb. 1:** Karte des untersuchten Gartens. Hecken und andere Baum- oder Strauchstrukturen sind **schwarz** umrahmt; Teiche und kleine Bäche **blau**; Trockenbereiche (beinhalten z.B. Steinhäufen, stehendes oder liegendes Totholz, Sandhügel sowie eine Ruderal- oder Pionierv egetation) **orange**; Trockensteinmauern **violett**; Brachflächen **braun**; Wiesen **gelb**; Saumvegetationsbereiche **ocker** und Gemüsegärten **rosa**.

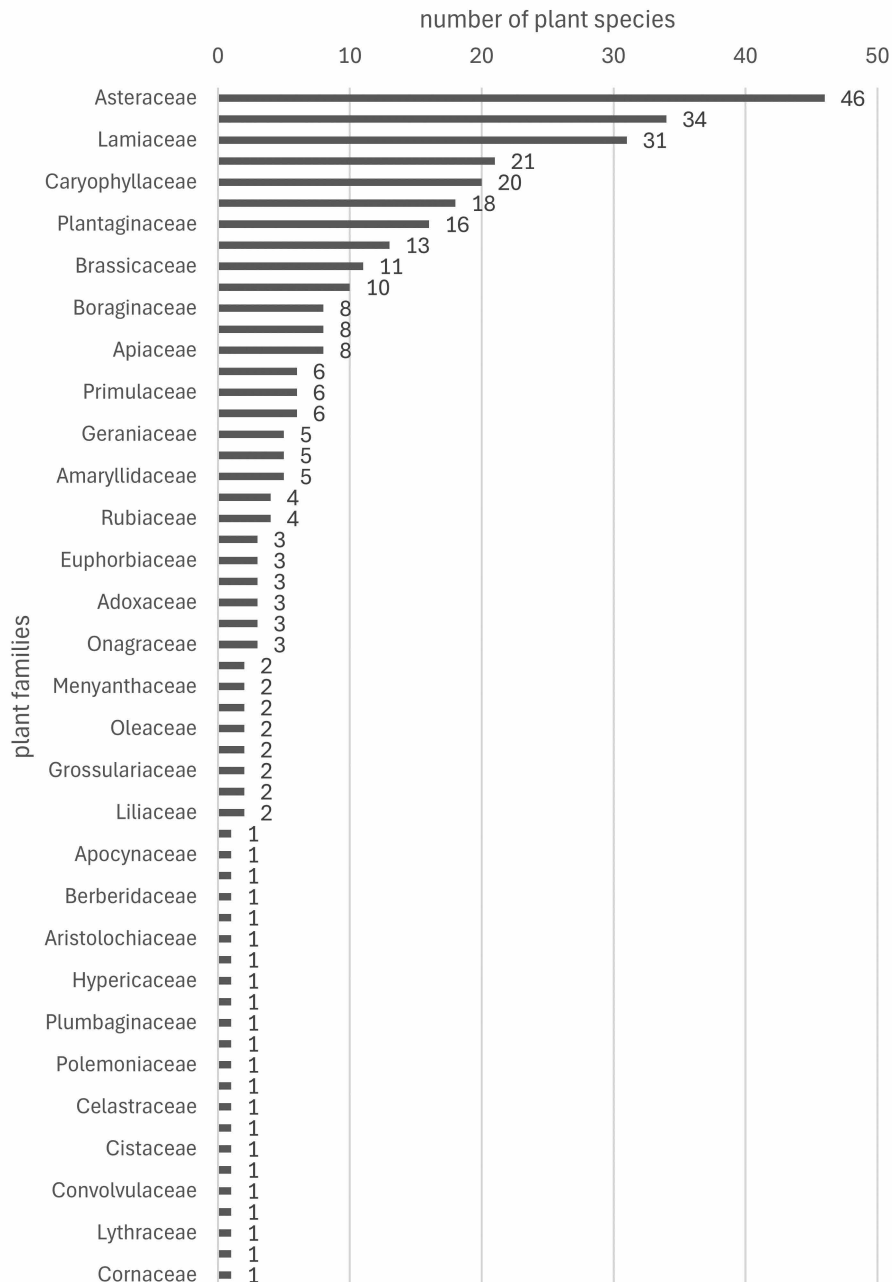


Fig. 2: Number of plant species per family of bee-relevant species flowering around the time of the bee survey days in 2024. | **Abb. 2:** Anzahl der während der Bienenbegehungstage in 2024 blühenden bienenrelevanten Pflanzenarten pro Pflanzenfamilie.



Fig. 3: Examples of nesting sites in the studied natural garden. **a, b:** sandy areas and small hills, **c:** vertically and horizontally placed dead or rotten wood, **d:** nesting aid mainly consisting of dead wood with drilled holes and hollow stems, **e:** various different nesting aids installed on the wall of a garden shed (e.g. dead wood with drilled holes and hollow stems, nesting aids that imitate vertical loess walls, vertically placed pithy stems and dead wood), **f:** nesting aid that imitates a vertical loess wall and contains dead wood structures. | **Abb. 3:** Beispiele für Nistmöglichkeiten im untersuchten Garten. **a, b:** sandige Flächen und Hügel, **c:** vertikal und horizontal ausgerichtetes Tot- und Morschholz, **d:** Nisthilfe hauptsächlich bestehend aus Totholz mit Bohrlöchern sowie hohlen Stängeln, **e:** verschiedenste Nisthilfen installiert an der Wand einer Gartenhütte (z.B. Nisthilfen bestehend aus Totholz mit Bohrlöchern sowie hohlen Stängeln; Nisthilfen, welche vertikale Lösswände imitieren; vertikal ausgerichtete markhaltige Stängel und stehendes Totholz), **f:** Nisthilfe, welche eine vertikale Lösswand imitiert, und zusätzlich Totholz-Strukturen enthält.

a biennial cycle. The meadows are mown 2 or 3 times a year, depending on the amount of nutrients they contain. In contrast to the meadows, the fringe vegetation areas are kept predominantly free of grass and get mown once a year at the end of vegetation period in autumn. In total, the garden approximately contains 72 square metres drystone walls and 92 stacked cubic metres stone piles including single rock structures. The total amount of deadwood in form of dead tree trunks, tree stumps and thicker branches starting from a diameter of about 5 cm is approximately 47 solid cubic metres. This high variety of different structures at a small-scale is enabled by the fact that the garden is modelled in the form of hills and depressions.

In the last few years, the management focused more and more on the promotion of wild bees by offering various different nesting sites and by introducing a high number of native plant species.

During the survey days in 2024, 341 bee-relevant plant species of 57 different families were flowering (Figure 2), among them >30 species each of Asteraceae, Rosaceae and Lamiaceae (Figure 2). Also highly represented with each between 21 to 10 flowering plant species were Fabaceae, Caryophyllaceae, Ranunculaceae, Plantaginaceae, Caprifoliaceae, Brassicaceae and Campanulaceae (Figure 2).

Nesting sites (Figure 3) were built by constructing sandy areas and small hills (Figure 3a,b), by placing pithy stems vertically (Figure 3e) and dead or rotten wood vertically and horizontally (Figure 3c), or by nesting aids consisting of dead wood with drilled holes or hollow stems (Figure 3d,e). In addition, nesting aids that imitate vertical loess walls were constructed and installed in the garden (Figure 3f).

Data collection and analysis

In order to investigate the wild bees, the garden (Figure 1) was surveyed in a total of seven days in 2024 (March 29; April 28; May 18; June 18; July 6; July 27, September 1), each from 10:00 to 16:00 by two persons, following a targeted netting approach. Bees that could be identified to species level in the field were either not collected or just one or a few individuals were collected, even if they were present in high abundances. In addition to this detailed survey, some bees were sporadically collected in 2021, 2022 and 2023. The collected bees were identified to species level using the following identification literature: Ebmer (1969,1970,1971,1973); Amiet (1996); Schmid-Egger and Scheuchl (1997); Scheuchl (2000); Amiet et al. (2001,2004); Scheuchl (2006); Amiet et al. (2007,2010); Bogusch and Straka (2012); Amiet et al. (2014); Dathe et al. (2016); Gokcezade et al. (2018); Praz et al. (2022). Several individuals were compared to bees available in reference collections at the Plant Ecology lab of the University of Salzburg and the Biodiversity Centre of Upper Austria in Linz. The managed honey bee *Apis mellifera*, which was also present in the garden, was not considered.

Nomenclature of the bees follows Scheuchl and Willner (2016), except for *Andrena afzeliella* and *Andrena stragulata*, which follows Praz et al. (2022) and Westrich (2019), respectively. Information on the biology and ecology of bees is primarily based on Westrich (2019), and for those species not mentioned in Westrich (2019), information is based on Wiesbauer

(2023) and/or Scheuchl and Willner (2016). For the evaluation of bees concerning their Red List status, the Red List of nearby Bavaria (Voith et al. 2021) was used as no Red list is available for (Upper) Austria. For four species not listed in the Bavarian Red List, the Red Lists of Switzerland (Müller & Praz 2024) and Germany (Westrich et al. 2011) were used.

The obtained bee data were compared with the data of three other studies performed in Upper Austria, i.e. in the Nature Park Mühlviertel (Schwarz et al. 2025), the Nature Park Obst-Hügel-Land (Ockermüller 2018), and the Botanical Garden Linz (Schwarz, personal communication, 2026), located at distances of about 35–55 km to the natural garden studied in the present work. The Nature Park Mühlviertel was surveyed on six days in 2011 and four days in 2025 (Schwarz et al. 2025), the Nature Park Obst-Hügel-Land on five days in 2017 (Ockermüller 2018), and the Botanical Garden Linz on five days each in 2023 and 2024 (Schwarz, personal communication, 2026).

Results

During the seven survey days in 2024, 663 wild bee individuals of 149 species were recorded (Table 1), whereas 29 further species were recorded during the sporadic surveys from 2021 to 2023, summing up to a total of 178 wild bee species for the garden (Table 1).

Of the 178 recorded species, 40 (22 %) were parasites and 138 (78 %) were nest-building. Among the nest-building bee species, 80 construct their nests in self-dug cavities in the soil (Figure 6a), followed by 23 and 21 species that build their nests in existing cavities (e.g. holes between or underneath rocks; crevices in stone) (Figure 6b) and existing cavities in dead wood (e.g. abandoned burrows of other insects), respectively (Figure 4). Seven species each nest in existing cavities in the soil (e.g. abandoned mice-burrows) and in self-made cavities in pithy stems (Figure 4; Figure 6c). Only a few species had other nesting behaviours (Figure 4; Figure 6d,e).

Forty-four (32 %) of the 138 nest-building bee species were oligoleges, specialized overall on 18 different plant families or genera, mostly on Asteraceae, Fabaceae, Campanulaceae or *Campanula* (Figure 5; Figure 6f).

In total, 39 (22 %) of the 178 bee species are threatened (categories 1, 2, 3, G, R), including five species each critically endangered and endangered (categories 1 and 2; Table 2). Eighteen (10 %) species are near threatened (category V; Table 2).

Most of the 178 recorded bee species have also been recorded in at least one of the studies performed in the Nature Park Mühlviertel (166 bee species recorded in total), the Nature Park Obst-Hügel-Land (96 bee species recorded in total), and the Botanical Garden Linz (128 bee species recorded in total). However, 29 species were exclusively found in the studied natural garden (Table 1, species marked in red).

Tab. 1: List of bee species recorded in 2024 and during the sporadic surveys between 2021 and 2023, including information on their nesting behaviour, sociality, lecty and Red List status of Bavaria (RL BY). For 2024, the number of collected individuals is given, for 2021-2023 the presence of a species is given. Bee species recorded in the studied natural garden but not in other studies recently performed in Upper Austria (Schwarz et al. 2025, Ockermüller 2018, Schwarz, personal communication) are highlighted in red. | **Tab. 1:** Artenliste der im Jahr 2024 oder während der sporadischen Begehungen von 2021 bis 2023 nachgewiesenen Bienenarten mit Informationen zur Nistweise, Sozialität, Pollenpräferenz und Rote Liste-Status Bayerns (RL BY). Für 2024 ist die Anzahl der gefangenen Individuen angegeben, für 2021-2023 dagegen die Präsenz einer Art. Bienenarten, die im untersuchten Naturgarten nachgewiesen wurden, aber in anderen kürzlich in Oberösterreich durchgeführten Studien (Schwarz et al. 2025, Ockermüller 2018, Schwarz, personal communication) nicht erfasst wurden, sind rot hervorgehoben.

species	2024	2021– 2023	nesting behaviour		sociality ³	oligo ⁵	RL BY
			under- ground ¹	over- ground ²			
<i>Andrena afzeliella</i> (KIRBY, 1802)	3		scs		?		LC ⁶
<i>Andrena agilissima</i> (SCOPOLI, 1770)		x	scs		co	Bra	3
<i>Andrena apicata</i> SMITH, 1847		x	scs		sl	Sal	G
<i>Andrena bicolor</i> FABRICIUS, 1775	11	x	scs		sl		*
<i>Andrena cineraria</i> (LINNAEUS, 1758)	2	x	scs		sl		*
<i>Andrena clarkella</i> (KIRBY, 1802)	1		scs		sl	Sal	*
<i>Andrena confinis</i> STOECKHERT, 1930	2		scs		?		D
<i>Andrena curvungula</i> THOMSON, 1870	1 [#]	x	scs		sl	Camc	2
<i>Andrena denticulata</i> (KIRBY, 1802)	5	x	scs		sl	Ast	V
<i>Andrena dorsata</i> (KIRBY, 1802)	11	x	scs		sl		*
<i>Andrena flavipes</i> PANZER, 1798	7	x	scs		sl		*
<i>Andrena fucata</i> SMITH, 1847		x	scs		sl		*
<i>Andrena fulva</i> (MÜLLER, 1766)	2 [#]	x	scs		sl		*
<i>Andrena fulvago</i> (CHRIST, 1791)	1		scs		sl	Ast	3
<i>Andrena gravida</i> IMHOFF, 1832	6	x	scs		sl		*
<i>Andrena haemorrhoa</i> (FABRICIUS, 1781)	13	x	scs		sl		*
<i>Andrena hattorfiana</i> (FABRICIUS, 1775)	3 [#]	x	scs		sl	Dip	3
<i>Andrena helvola</i> (LINNAEUS, 1758)	5		scs		sl		*
<i>Andrena humilis</i> IMHOFF, 1832	5		scs		sl	Ast	V
<i>Andrena labiata</i> FABRICIUS, 1781	4 [#]	x	scs		sl		*
<i>Andrena lathyri</i> ALFKEN, 1899		x	scs		sl	Lat, Vic	V
<i>Andrena minutula</i> (KIRBY, 1802)	8		scs		sl		*

species	2024	2021– 2023	nesting behaviour		sociality ³	oligo ⁵	RL BY
			under- ground ¹	over- ground ²			
<i>Andrena minutuloides</i> PERKINS, 1914	2		scs		sl		*
<i>Andrena nigroaenea</i> (KIRBY, 1802)	1		scs		sl		*
<i>Andrena nitida</i> (MUELLER, 1776)		x	scs		sl		*
<i>Andrena nitidiuscula</i> SCHENCK, 1853	2		scs		sl	Api	3
<i>Andrena pandellei</i> PÈREZ, 1895		x	scs		sl	Camp	3
<i>Andrena paucisquama</i> NOSKIEWICZ, 1924	1		scs		sl	Camc	17
<i>Andrena praecox</i> (SCOPOLI, 1763)	5	x	scs		sl	Sal	*
<i>Andrena proxima</i> (KIRBY, 1802)	3		scs		sl	Api	*
<i>Andrena rosae</i> PANZER, 1801	1 [#]	x	Scs		sl	Api	1
<i>Andrena scotica</i> PERKINS, 1916	3		scs		co		*
<i>Andrena stragulata</i> ILLIGER, 1806	1		scs		sl		37
<i>Andrena strohmei</i> STÖCKHERT, 1928		x	scs		sl		*
<i>Andrena subopaca</i> NYLANDER, 1848	8		scs		sl		*
<i>Andrena susterai</i> ALFKEN, 1914		x	scs		sl		R
<i>Andrena synadelpha</i> PERKINS, 1914	1		scs		sl		G
<i>Andrena viridescens</i> VIERECK, 1916	1		scs		sl	Ver	V
<i>Andrena wilkella</i> (KIRBY, 1802)	13		scs		sl	Fab	*
<i>Anthidiellum strigatum</i> (PANZER, 1805)	1	x		f	sl		V
<i>Anthidium manicatum</i> (LINNAEUS, 1758)	8 [#]	x		oec	sl		*
<i>Anthidium oblongatum</i> (ILLIGER, 1806)	7 [#]	x		oec	sl		*
<i>Anthidium punctatum</i> LATREILLE, 1809	4 [#]	x		oec	sl		*
<i>Anthophora aestivalis</i> (PANZER, 1801)	1	x	scs		sl		3
<i>Anthophora crinipes</i> SMITH, 1854	3	x	scs		sl		R
<i>Anthophora furcata</i> (PANZER, 1798)	4	x		rw	sl	Lam	V
<i>Anthophora plumipes</i> (PALLAS, 1772)	1 [#]	x	scs		sl		*
<i>Anthophora quadrimaculata</i> (PANZER, 1798)	3	x	scs		sl		3
<i>Bombus bohemicus</i> SEIDL, 1838	1				pa		*
<i>Bombus campestris</i> (PANZER, 1801)	2				pa		*
<i>Bombus hortorum</i> (LINNAEUS, 1761)	2 [#]	x	ecs	oec	sc		*

species	2024	2021– 2023	nesting behaviour		sociality ³	oligo ⁵	RL BY
			under- ground ¹	over- ground ²			
<i>Bombus humilis</i> (ILLIGER, 1806)	2	x		hl	sc		3
<i>Bombus hypnorum</i> (LINNAEUS, 1758)	1 [#]	x		oec	sc		*
<i>Bombus lapidarius</i> (LINNAEUS, 1758)	2 [#]	x	ecs	oec	sc		*
<i>Bombus lucorum</i> (LINNAEUS, 1761)	5 [#]	x	ecs		sc		*
<i>Bombus norvegicus</i> (SPARRE-SCHNEIDER, 1918)	2				pa		*
<i>Bombus pascuorum</i> (SCOPOLI, 1763)	4 [#]	x	ecs	oec	sc		*
<i>Bombus pratorum</i> (LINNAEUS, 1761)	3 [#]	x		oec	sc		*
<i>Bombus terrestris</i> (LINNAEUS, 1758)	4 [#]	x	ecs		sc		*
<i>Ceratina chalybea</i> CHEVRIER, 1872	1			ps	sl		3
<i>Ceratina cucurbitina</i> (ROSSI, 1792)		x		ps	sl		*
<i>Ceratina cyanea</i> (KIRBY, 1802)	9	x		ps	sl		*
<i>Chelostoma campanularum</i> (KIRBY, 1802)	7	x		ecw	sl	Camp	*
<i>Chelostoma distinctum</i> (STOECKHERT, 1929)	9	x		ecw	sl	Camp	*
<i>Chelostoma emarginatum</i> (NYLANDER, 1856)	1			ecw	sl	Ran	CR ⁶
<i>Chelostoma florissomme</i> (LINNAEUS, 1758)	5	x		ecw	sl	Ran	*
<i>Chelostoma rapunculi</i> (LEPELETIER, 1841)	7	x		ecw	sl	Camp	*
<i>Coelioxys alata</i> FÖRSTER, 1853	2				pa		*
<i>Coelioxys aurolimbata</i> FÖRSTER, 1853	1				pa		3
<i>Coelioxys conoidea</i> (ILLIGER, 1806)	1	x			pa		3
<i>Coelioxys elongata</i> LEPELETIER, 1841		x			pa		*
<i>Coelioxys rufescens</i> LEPELETIER & SERVILLE, 1825	5	x			pa		3
<i>Colletes daviesanus</i> SMITH, 1846	7		scs		sl	Ast	*
<i>Colletes hederæ</i> SCHMIDT & WESTRICH, 1993	2		scs		sl	Hed	*
<i>Colletes similis</i> SCHENCK, 1853	3		scs		sl	Ast	V
<i>Dioxys cincta</i> (JURINE, 1807)	3 [#]				pa		R
<i>Epeoloides coecutiens</i> (FABRICIUS, 1775)		x			pa		*
<i>Eucera longicornis</i> (LINNAEUS, 1758)		x	scs		sl	Fab	V

species	2024	2021– 2023	nesting behaviour		sociality ³	oligo ⁵	RL BY
			under- ground ¹	over- ground ²			
<i>Halictus confusus perkinsi</i> BLÜTHGEN, 1926	2		scs		sc		*
<i>Halictus maculatus</i> SMITH, 1848	9	x	scs		sl		*
<i>Halictus rubicundus</i> (CHRIST, 1791)	1		scs		sl, sc		*
<i>Halictus scabiosae</i> (ROSSI, 1790)	2 [#]	x	scs		sl		*
<i>Halictus sexcinctus</i> (FABRICIUS, 1775)	10 [#]	x	scs		sl		V
<i>Halictus simplex</i> BLÜTHGEN, 1923	9		scs		sl		*
<i>Halictus subauratus</i> (ROSSI, 1792)	26	x	scs		sc		*
<i>Halictus tumulorum</i> (LINNAEUS, 1758)	10	x	scs		sc		*
<i>Heriades truncorum</i> (LINNAEUS, 1758)	15	x		ecw	sl	Ast	*
<i>Hoplitis adunca</i> (PANZER, 1798)	13	x		ecw	sl	Ech	*
<i>Hoplitis anthocopoides</i> (SCHENCK, 1853)	1			f	sl	Ech	3
<i>Hoplitis claviventris</i> (THOMSON, 1872)	1			ps	sl		*
<i>Hoplitis leucomelana</i> (KIRBY, 1802)	8	x		ps	sl		*
<i>Hoplitis mitis</i> (NYLANDER, 1852)	2 [#]			hl	sl	Camp	2
<i>Hoplitis tridentata</i> (DUFOR & PERRIS, 1840)	4 [#]	x		ps	sl	Fab	*
<i>Hylaeus brevicornis</i> NYLANDER, 1852	1			oec	sl		*
<i>Hylaeus communis</i> NYLANDER, 1852	15	x		oec	sl		*
<i>Hylaeus confusus</i> NYLANDER, 1852	10			ecw, ps	sl		*
<i>Hylaeus difformis</i> (EVERSMANN, 1852)	6	x		oec	sl		*
<i>Hylaeus dilatatus</i> (KIRBY, 1802)	6			oec	sl		*
<i>Hylaeus gredleri</i> FÖRSTER, 1871	1			ecw	sl		*
<i>Hylaeus hyalinatus</i> (SMITH, 1842)	11			oec	sl		*
<i>Hylaeus nigrinus</i> (FABRICIUS, 1798)	8			oec	sl	Ast	*
<i>Hylaeus paulus</i> BRIDWELL, 1919	6			oec	sl		D
<i>Hylaeus punctatus</i> (BRULLÉ, 1832)	1			oec	sl		*
<i>Hylaeus sinuatus</i> (SCHENCK, 1853)	2	x		oec	sl		*
<i>Hylaeus styriacus</i> FÖRSTER, 1871	1			oec	sl		*
<i>Hylaeus signatus</i> (PANZER, 1798)		x		oec	sl	Res	*
<i>Lasioglossum albipes</i> (FABRICIUS, 1781)	6	x	scs		?		*

species	2024	2021– 2023	nesting behaviour		sociality ³	oligo ⁵	RL BY
			under- ground ¹	over- ground ²			
<i>Lasioglossum calceatum</i> (SCOPOLI, 1763)	11	x	scs		sc		*
<i>Lasioglossum costulatum</i> (KRIECHBAUMER, 1873)	1		scs		sl	Camc	V
<i>Lasioglossum fulvicorne</i> (KIRBY, 1802)	2		scs		sl		*
<i>Lasioglossum intermedium</i> (SCHENCK, 1869)		x	scs		?		3
<i>Lasioglossum laticeps</i> (SCHENCK, 1869)	6		scs		sc		*
<i>Lasioglossum leucozonium</i> (SCHRANK, 1781)	3	x	scs		sl		*
<i>Lasioglossum marginatum</i> (BRULLÈ, 1832)		x	scs		sc		R
<i>Lasioglossum morio</i> (FABRICIUS, 1793)	27	x	scs		sc ⁴		*
<i>Lasioglossum nigripes</i> (LEPELETIER, 1841)	8		scs		sc		1
<i>Lasioglossum nitidiusculum</i> (KIRBY, 1802)		x	scs		sl		V
<i>Lasioglossum nitidulum</i> (FABRICIUS, 1804)	4		scs		sl		*
<i>Lasioglossum parvulum</i> (SCHENCK, 1853)		x	scs		sl		V
<i>Lasioglossum pauxillum</i> (SCHENCK, 1853)	16		scs		sc		*
<i>Lasioglossum politum</i> (SCHENCK, 1853)	1		scs		sc		*
<i>Lasioglossum rufitarse</i> (ZETTERSTEDT, 1838)	1	x	scs		sl		*
<i>Lasioglossum villosulum</i> (KIRBY, 1802)	2		scs		sl		*
<i>Lasioglossum zonulum</i> (SMITH, 1848)	1	x	scs		sl		*
<i>Macropis europaea</i> WARNCKE, 1973	4 [#]	x	scs		sl	Lys	*
<i>Macropis fulvipes</i> (FABRICIUS, 1804)	6 [#]		scs		sl	Lys	*
<i>Megachile alpicola</i> ALFKEN, 1924		x		ecw	sl		*
<i>Megachile centuncularis</i> (LINNAEUS, 1758)	3			ecw	sl		V
<i>Megachile circumcincta</i> (KIRBY, 1802)	1	x		ecw, oec	sl		V
<i>Megachile ericetorum</i> LEPELETIER, 1841	8 [#]	x		oec	sl	Fab	*
<i>Megachile lagopoda</i> (LINNAEUS, 1761)	8 [#]	x	ecs		sl		2
<i>Megachile ligniseca</i> (KIRBY, 1802)	2	x		ecw	sl		3
<i>Megachile nigriventris</i> SCHENCK, 1869	2	x		rw	sl		*
<i>Megachile rotundata</i> (FABRICIUS, 1787)	3			ecw	sl		*

species	2024	2021– 2023	nesting behaviour		sociality ³	oligo ⁵	RL BY
			under- ground ¹	over- ground ²			
<i>Megachile versicolor</i> SMITH, 1844	3	x	ecs	ecw	sl		*
<i>Megachile willughbiella</i> (KIRBY, 1802)	4	x	scs	ecw	sl		*
<i>Melecta albifrons</i> (FORSTER, 1771)	2 [#]	x			pa		V
<i>Melitta haemorrhoidalis</i> (FABRICIUS, 1775)	4 [#]	x	scs		sl	Camc	*
<i>Melitta nigricans</i> ALFKEN, 1905	3 [#]	x	scs		sl	Lyt	V
<i>Nomada armata</i> HERRICH-SCHÄFFER, 1839		x			pa		2
<i>Nomada femoralis</i> MORAWITZ, 1868		x			pa		1
<i>Nomada ferruginata</i> (LINNAEUS, 1767)		x			pa		*
<i>Nomada flava</i> PANZER, 1798		x			pa		*
<i>Nomada flavoguttata</i> (KIRBY, 1802)	1	x			pa		*
<i>Nomada flavopicta</i> (KIRBY, 1802)		x			pa		*
<i>Nomada fulvicornis</i> FABRICIUS, 1793	1	x			pa		*
<i>Nomada fuscicornis</i> NYLANDER, 1848	1				pa		3
<i>Nomada panzeri</i> LEPELETIER, 1841	1	x			pa		*
<i>Nomada ruficornis</i> (LINNAEUS, 1758)	4				pa		*
<i>Nomada signata</i> JURINE, 1807		x			pa		*
<i>Nomada stigma</i> FABRICIUS, 1804		x			pa		3
<i>Nomada striata</i> FABRICIUS, 1793		x			pa		*
<i>Osmia aurulenta</i> (PANZER, 1799)	3 [#]	x		ss	sl		*
<i>Osmia bicolor</i> (SCHRANK, 1781)	2	x		ss	sl		*
<i>Osmia bicornis</i> (LINNAEUS, 1758)	9 [#]	x		ecw, oec	sl		*
<i>Osmia caerulea</i> (LINNAEUS, 1758)	13	x		ecw	sl		*
<i>Osmia cornuta</i> (LATREILLE, 1805)	field	x		ecw, oec	sl		*
<i>Osmia leaiana</i> (KIRBY, 1802)	20	x		ecw	sl	Ast	3
<i>Osmia niveata</i> (FABRICIUS, 1804)	1			ecw	sl	Ast	3
<i>Panurgus calcaratus</i> (SCOPOLI, 1763)	2 [#]	x	scs		co	Ast	V
<i>Sphecodes albilabris</i> (FABRICIUS, 1793)		x			pa		*
<i>Sphecodes crassus</i> THOMSON, 1870	1	x			pa		*
<i>Sphecodes ephippius</i> (LINNAEUS, 1767)	7	x			pa		*

species	2024	2021– 2023	nesting behaviour		sociality ³	oligo ⁵	RL BY
			under- ground ¹	over- ground ²			
<i>Sphecodes gibbus</i> (LINNAEUS, 1758)		x			pa		*
<i>Sphecodes longulus</i> Hagens, 1882	1				pa		*
<i>Sphecodes monilicornis</i> (KIRBY, 1802)	2				pa		*
<i>Sphecodes niger</i> Hagens, 1874	1				pa		*
<i>Sphecodes puncticeps</i> THOMSON, 1870		x			pa		*
<i>Sphecodes reticulatus</i> THOMSON, 1870	1				pa		V
<i>Stelis breviuscula</i> (NYLANDER, 1848)	1				pa		*
<i>Stelis minima</i> SCHENCK, 1859	3	x			pa		D
<i>Stelis minuta</i> LEPELETIER & SERVILLE, 1825	1	x			pa		3
<i>Stelis ornatula</i> (KLUG, 1807)	2				pa		*
<i>Stelis phaeoptera</i> (KIRBY, 1802)	1	x			pa		2
<i>Stelis punctulatissima</i> (KIRBY, 1802)	3 [#]	x			pa		*
<i>Stelis signata</i> (LATREILLE, 1809)	1	x			pa		3
<i>Trachusa byssina</i> (PANZER, 1804)	2		scs		sl	Fab	3
<i>Xylocopa violacea</i> (LINNAEUS, 1758)	field	x		rw	sl		*

Only a subset of individuals recorded in the garden have been collected.

1 underground nesting behaviours: ecs: existing cavities in the soil; scs: self-dug cavities in the soil.

2 overground nesting behaviours: ecw: existing cavities in dead wood or cavities in hollow stems; oec: other existing cavities; ps: self-made cavities in pithy stems; rw: self-made cavities in rotting wood; f: free-standing nests; hl: herb layer; ss: empty snail shells.

3 sociality: sl: solitary; co: communal; sc: social; pa: cleptoparasitic or social parasitic; ?: the sociality of these nest-building bee species is unknown

4 The sociality was suggested but not proven.

5 oligo: oligolectic; Bra: Brassicaceae; Sal: *Salix*; Camp: *Campanula*; Camc: *Campanulaceae*; Ast: Asteraceae; Dip: Dipsacaceae; Lat: *Lathyrus*; Vic: *Vicia*; Api: Apiaceae; Ver: *Veronica*; Fab: Fabaceae; Lam: Lamiaceae; Ran: *Ranunculus*; Hed: *Hedera*; Ech: *Echium*; Res: *Reseda*; Lys: *Lysimachia*; Lyt: *Lythrum*; if the cell is empty for a species and if this species is not marked as parasitic, it is polylectic.

6 Müller and Praz (2024)

7 Westrich et al. (2011)

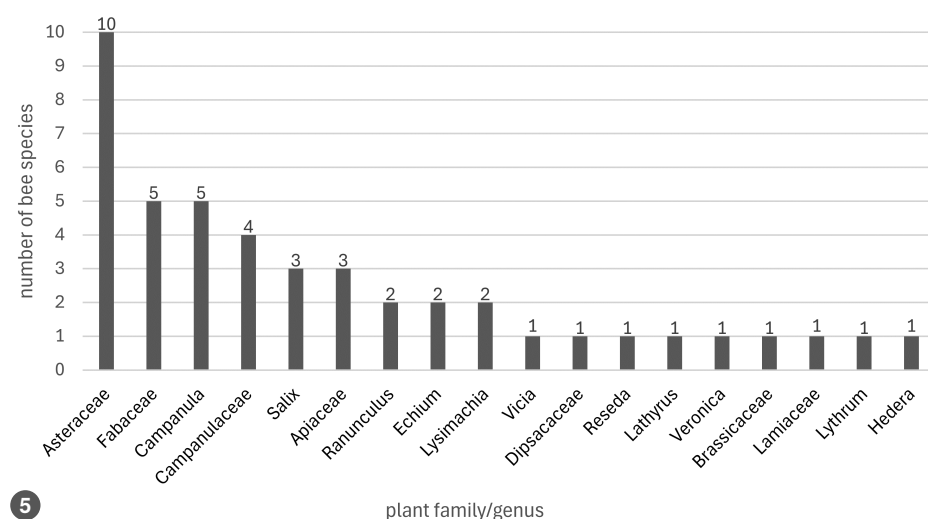
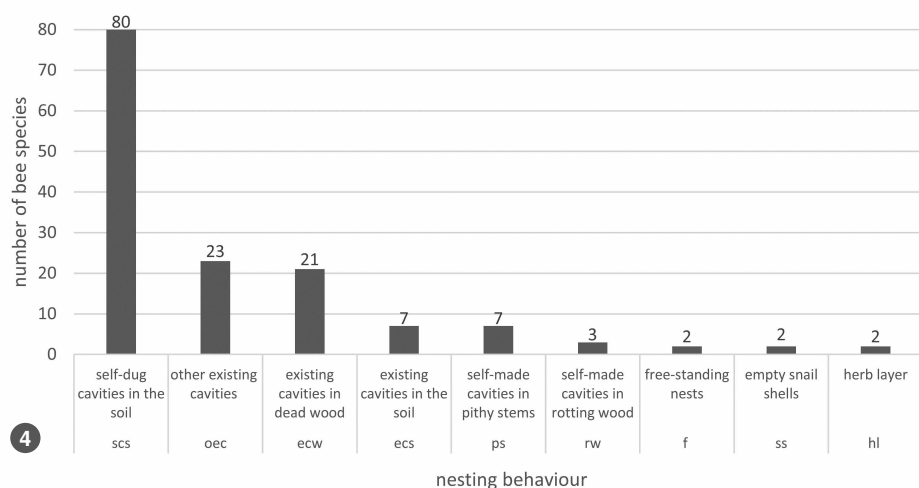


Fig. 4: Nesting behaviour of the 138 recorded nest-building bee species (several bee species are classified in different categories (Table 1)). The abbreviations are the same as given in Table 1. | **Abb. 4:** Nistweisen der 138 nachgewiesenen nestbauenden Bienenarten (einige Arten sind mehreren Kategorien zugeordnet, s. Tabelle 1). Die Abkürzungen entsprechen denen in Tabelle 1.

Fig. 5: Pollen sources of the 44 recorded oligolectic species (the bee species *Andrena lathyri* is listed twice, namely once for *Lathyrus* and once for *Vicia* (Table 1)). | **Abb. 5:** Pollenquellen der 44 nachgewiesenen oligolektischen Bienenarten (*Andrena lathyri* wurde zweimal zugeteilt, nämlich den Pflanzengattungen *Lathyrus* und *Vicia*, s. Tabelle 1).



Fig. 6: Examples of the recorded bee species. **a:** *Panurgus calcaratus*, which constructs its nests in self-dug cavities in the soil, next to a nest entrance, **b:** *Anthidium punctatum*, which builds its nests in existing cavities, sitting on a flower of *Cichorium intybus*, **c:** *Hoplitis tridentata* at the entrance of its nest in a self-made cavity in a pithy stem, **d:** *Osmia bicolor* while constructing its nest in an empty snail shell, **e:** *Xylocopa violacea*, which nests in self-made cavities in rotten wood, visiting flowers of *Carduus nutans*, **f:** *Melitta nigricans*, an oligolectic bee species, visiting flowers of *Lythrum salicaria*. | **Abb. 6:** Beispiele nachgewiesener Bienenarten. **a:** *Panurgus calcaratus*, die ihre Nester in selbstgegrabenen Hohlräumen im Boden anlegt, neben einem Nesteingang, **b:** *Anthidium punctatum*, welche ihre Nester in bereits bestehenden Hohlräumen anlegt, auf einer Blüte von *Cichorium intybus* sitzend, **c:** *Hoplitis tridentata* am Eingang ihres Nestes in einem selbstgenagten Hohlraum in einem markhaltigen Stängel, **d:** *Osmia bicolor* beim Bau ihres Nestes in einem leeren Schneckenhaus, **e:** *Xylocopa violacea*, die in selbstgenagten Hohlräumen in Morschholz nistet, beim Besuch einer Blüte von *Carduus nutans*, **f:** *Melitta nigricans*, eine oligolectische Bienenart, beim Besuch der Blüten von *Lythrum salicaria*.

Tab. 2: Number of recorded bee species for the different Red List categories. | **Tab. 2:** Anzahl der nachgewiesenen Bienenarten pro Rote-Liste-Kategorie.

Red List category	number of bee species
1 (critically endangered)	5 ¹
2 (endangered)	5
3 (vulnerable)	23
G (threatened to an unknown extent)	2
R (extremely rare)	4
V (near threatened)	18
* (least concern)	118 ²
D (data deficient)	3

- 1 including the category CR of the Red List of Switzerland (Table 1)
- 2 including the category LC of the Red List of Switzerland (Table 1)

Discussion

With a total of 178 recorded wild bee species, the number of species in this garden accounts for a quarter (25 %) of the bee species recorded throughout Austria (Wiesbauer 2023) and for about two-fifths (41 %) of those recorded for Upper Austria (Gusenleitner et al. 2012; Ebmer et al. 2018; Ockermüller et al. 2021; Schwarz & Schwarz 2024). Of the 178 recorded wild bee species, 22 % were parasites and 78 % were nest-building. 32 % of the nest-building bee species were oligoleges. Most of the nest-building species construct their nests in self-dug cavities in the soil, in existing cavities or in existing cavities in dead wood. 22 % of the recorded bee species are threatened according to the Red List.

A total of 29 bee species were recorded in the studied natural garden but not in other studies recently performed in Upper Austria (Table 1, species marked in red). Among them are species such as *Hoplitis tridentata*, *Anthophora quadrimaculata*, *Lasioglossum costulatum*, *Lasioglossum intermedium* and *Coelioxys alata*. *Hoplitis tridentata* is an oligolectic bee species specialised on Fabaceae, and constructs its nests in self-made cavities in pithy stems (Westrich 2019). *Anthophora quadrimaculata* is polylectic and constructs its nests in self-dug cavities in the soil, preferably in vertical loess or clay walls (Westrich 2019). Such nesting sites are provided in the garden by nesting aids that imitate vertical loess and clay walls and by sandy areas/hills. *Lasioglossum costulatum* is specialised for its pollen on Campanulaceae and constructs its nests in self-dug cavities in the soil (Westrich 2019). This species benefits from the high number of different plant species of native Campanulaceae which were introduced into the garden. *Lasioglossum intermedium* is polylectic and nests in self-dug cavities in sandy soil (Westrich 2019). Such nesting sites are provided by the high variety of sandy areas and small hills in the garden. *Coelioxys alata* is a parasitic bee species and specialised on its host species *Megachile ligniseca*, which was also recorded in the Garden (Westrich 2019). Furthermore, our study provides confirmed records of *Megachile lagopoda* (LINNAEUS, 1761) for Upper Austria, a species that had not previously been reliably documented in this

Tab. 3: Size, total number of bee species and number of bee species per 100 m² of three botanical gardens. | **Tab. 3:** Fläche, Gesamtanzahl nachgewiesener Bienenarten und Anzahl an Bienenarten pro 100 m² dreier Botanischer Gärten.

study area	area (m ²)	number of bee species	number of bee species per 100 m ²	Reference
Botanical Garden Bayreuth	135.000	228	0.2	Schanz et al. (2023)
Botanical Garden Graz	36.000	151	0.4	Teppler et al. (2016)
Botanical Garden Vienna	80.000	131	0.2	Hölzler (2004)

federal state (Gusenleitner et al. 2012; Ebmer et al. 2018; Ockermüller et al. 2021; Schwarz & Schwarz 2024). Verified records have also recently been reported from the Nature Park Mühlviertel (Schwarz et al. 2025). Overall, the natural garden is home for a high number of bees available in the region. The high number of flowers and nesting sites offered in the garden obviously also allowed bees otherwise rare in Upper Austria to colonize the garden.

When comparing the bee fauna recorded in this garden with that of the Botanical Garden Bayreuth (Germany), which is the botanical garden with the highest number of recorded bee species so far, and the two Austrian botanical gardens with available data (Graz and Vienna) (Table 3), the two Austrian botanical gardens show lower species numbers (≤ 151 species), whereas the Botanical Garden of Bayreuth has a higher species number, with 228 bee species recorded. Considering the different sizes of the three botanical gardens (36000–135000 m²; Table 3) and the studied natural garden (3700 m²), it is obvious that the relatively small natural garden contains a remarkably diverse bee fauna (approximately 5 species per 100 m²) when compared to the botanical gardens (0.2–0.4 species per 100 m²) (Table 3).

The percentage of parasitic bee species (22 %) observed in this garden is comparable to that reported for the bee fauna of Germany, Austria and Switzerland (Wiesbauer 2023), as well as to proportions found in botanical gardens (e.g. 24 % for the Botanical Garden of Vienna, (Hölzler 2004); 29 % for the Botanical Garden Bayreuth in 2022, (Schanz 2023)). This suggests that the surveyed garden contains stable populations of the necessary hosts and serves as a high quality habitat also for bee species with specialised life history requirements (Bell et al. 2023). This conclusion that the surveyed garden is not only suitable for generalists but also for specialists is supported by the finding that approximately one third of the nest-building species were oligoleges. Again, this number is similar to the proportion of oligoleges among all the nest-building wild bee species of Germany, Austria and Switzerland (Wiesbauer 2023), and to the proportion of oligoleges in botanical gardens (e.g. 30 % for the Botanical Garden Vienna, (Hölzler 2004); 33 % for the Botanical Garden Bayreuth in 2022, (Schanz 2023)). This high proportion of oligolectic species, and the high wild bee species richness in general, is very likely possible due to the high abundance, number and taxonomic diversity of flowering plant species available in the garden (Rahimi et al. 2022; Rotondi et al. 2024). Interestingly, most of the recorded oligoleges are specialised on Asteraceae, which is also the family which showed the highest abundance of blooming flowering plants in the garden. Similarly, the recorded fauna contained a high number of oligolectic species specialised on the genus *Campanula* or on Campanulaceae, of which 10 species have bloomed in the garden. This suggests that the species richness of plant families affects the number of oligoleges recorded on these plants. This conclusion is supported by

the fact that among those oligolectic bee species which are specialised on Asteraceae, for instance, some bee species are showing preferences for specific plant tribes, genera or species within the family and favour them over other such groups (Westrich 2019). Due to these further specialisations of oligolectes within a plant family, a garden that hosts a higher species richness of native plants per family therefore is very likely to promote a higher number of different oligolectes.

Our finding that most of the recorded species build their nests in self-dug cavities in the soil, in other existing cavities (e.g. holes between or underneath rocks; crevices in stone) and in existing cavities in dead wood (e.g. abandoned burrows of other insects) suggests that the bees accepted the various nesting aids offered in the garden. However, more research is needed to record the nesting sites of the different species and test which of them do indeed nest in the garden.

Our finding that 22 % of all recorded wild bee species can be classified as threatened (Red List categories 1, 2, 3, G, R) – a proportion slightly higher than that reported for the Botanical Garden in Bayreuth (approximately 19 % of the 228 recorded species; Schanz et al. 2023) – indicates that in this garden not only common but also rare and endangered species are present.

To conclude, this study shows that there is a high potential of highly structured private natural gardens in supporting and promoting a high diversity of bees in times, where this important group of pollinators is declining in Europe and around the globe (IPBES 2016, Michez et al. 2026). This not only is shown by the high number of 178 different bee species recorded in this garden but also by the fact that among them, there were not only common and generalist species, but also many rare, endangered and highly specialised ones. To the best of our knowledge, there is no other private garden in Central Europe known that has such a high species richness of bees. With a theoretical number of approximately 5 bee species per 100 m², this garden hosts a remarkably diverse bee fauna on a relatively small area. This high species richness of wild bees is particularly remarkable given the fact that the garden is rather young, with the majority of structures built within the last 10 years. Thus, it is likely that additional species will establish themselves in the future. This assumption that additional bee species will establish over time is indeed supported by the fact that in 2025, a further ten species were newly recorded for the garden during sporadic surveys: *Andrena alutacea* STÖCKHERT, 1942; *Andrena fulvata* STÖCKHERT, 1930; *Andrena varians* (KIRBY, 1802); *Bombus mastrucatus* GERSTÄCKER, 1869; *Bombus barbutellus* (KIRBY, 1802); *Coelioxys inermis* (KIRBY, 1802); *Epeolus variegatus* (LINNAEUS, 1758); *Hylaeus cornutus* CURTIS, 1831; *Lasioglossum semilucens* (ALFKEN, 1914); and *Nomada marshamella* (KIRBY, 1802). With these additions, the total number of recorded wild bee species currently amounts to 188. The comparison with several botanical gardens revealed that, although they may support a similarly high or even higher total species richness, this occurs on significantly larger areas, and most botanical gardens have also been established for a far longer time (e.g. Dötterl 2001; Hölzler 2004; Teppner et al. 2016; Schanz 2023). To better understand which measures taken in this garden contribute most to the promotion of wild bees and which have lesser effects, further research is necessary. It would be very interesting to know which of the plant species are used by which bees as host plants, and which of the nesting sites and nesting aids available in the garden are used by the different bees. Such data could be a basis for suggesting conservation measures for bees in private gardens and elsewhere.

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Die Auswirkungen des Klimawandels auf Libellen und die angewandte odonatologische Forschung (Insecta: Odonata)

Andreas Chovanec ¹

In der der jüngeren Vergangenheit wurden in mehreren Studien aus Ost-Österreich Auswirkungen des Klimawandels auf Libellen dokumentiert. Im vorliegenden Beitrag sind diese komplexen Effekte zusammengefasst und diskutiert. Veränderungen des Verbreitungsgebietes werden am Beispiel von *Erythromma lindenii* beschrieben. Männchen von *Orthetrum cancellatum* und *Orthetrum coerulescens* reagieren auf erhöhte Temperaturen und UV-Strahlung mit intensiver Blaubereifung des Thorax. Auch erste Nachweise verstärkter thorakaler Rotfärbung bei *Sympetrum sanguineum* geben möglicherweise Hinweise auf derartige klinale Veränderungen. Bei Arten aller phänologischen Gilden sind Verschiebungen von Emergenz-, Reifungs- und Flugzeiten festzustellen. Die Fundsituation von *Aeshna affinis* im Jahr 2024 zeigt, dass unter bestimmten Voraussetzungen hydrologische Extremereignisse dem klimawandelbedingten Habitatverlust entgegenwirken können. Implikationen dieser Auswirkungen auf die Methodik odonatologischer Erhebungen, auf die Definition ökologischer und phänologischer Gilden, auf Bioindikationsverfahren und Gefährdungseinstufungen werden dargestellt.

Chovanec A (2026) Effects of climate change on dragonflies and on applied odonatological research (Insecta: Odonata)

In the recent years, several studies carried out in Eastern Austria document impacts of climate change on Odonata. In the present paper, these complex effects are summarised and discussed. Changes of the distribution area are illustrated using the example of *Erythromma lindenii*. Male *Orthetrum cancellatum* and *Orthetrum coerulescens* respond to increased temperatures and UV-radiation with strong thoracic pruinescence. First records of male *Sympetrum sanguineum* with a red coloured thorax may also indicate clinal phenotypic variations due to climate change. Species of all phenological guilds show changes in life-history traits, such as shifts in emergence, maturation, and flight periods. In 2024, records of *Aeshna affinis* proved, that – under certain conditions – extreme hydrological events counteract climate-induced habitat loss. Implications of these climate-based effects on the methodology of odonatological surveys, on the definition of ecological and phenological guilds, on bioindication methods, and on the assessment of the species' threat status are presented.

Keywords: climate change, Odonata, range shift, distribution, phenology, pruinescence, UV-radiation, temperature, clinal variation.

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Einleitung

Die komplexen Folgen des Klimawandels auf die Libellenfauna sind seit Jahren Gegenstand der Fachliteratur und beziehen sich sowohl auf die aquatische als auch die terrestrische Lebensphase von Vertretern dieser Insektenordnung und die entsprechenden Teillebensräume (Hassall & Thompson 2008; Cancellario et al. 2022; Pinkert et al. 2023; Castillo-Pérez et al. 2024). Sie betreffen Veränderungen der horizontalen sowie vertikalen Verbreitung (Ott 2010; Hassall 2015; Basel et al. 2021; Lemke 2021; Bowler et al. 2022; Péliissié et al. 2022;

Cadena et al. 2023; Hawkes et al. 2024; Holmes 2025) und haben Einfluss auf Phänologie, Entwicklungsgeschwindigkeiten und Voltinismus (Thomas 2002; Kunz & Hunger 2006; Hassall et al. 2007; Schirmacher et al. 2007; Flenner et al. 2010; McCauley et al. 2018; Patton & Benson 2023; Maynou et al. 2025). Hervorzuheben sind ebenso Effekte auf zwischenartliche Interaktionen und Konkurrenzphänomene sowohl zwischen etablierten und „neuen“ Arten als auch zwischen seit langem etablierten Spezies (Suhling & Suhling 2013; Hogreve & Suhling 2022; Stahl & Johansson 2024) und Implikationen auf Körpergröße und Morphologie (Hassall et al. 2009; McCauley et al. 2018; Acquah-Lamprey et al. 2020; Wonglersak et al. 2020). Sánchez-Guillén et al. (2016, 2024) beschrieben Zusammenhänge zwischen Klimawandel, Molekularbiologie und Hybridisierung. Die Auswirkungen auf die Reproduktionslebensräume von Libellen sind z.T. dramatisch (Bush et al. 2014; Theischinger et al. 2021). Daher ist jedenfalls zu diskutieren, ob Arten mit vergrößertem Verbreitungsgebiet zu „Gewinnern des Klimawandels“ zu zählen sind, wenn die Habitatverfügbarkeit insbesondere in südlichen Teilen ihres Areals durch schnelleres Austrocknen der Gewässer signifikant reduziert ist (De Knijf et al. 2024a). Diese Prozesse werden durch anthropogene Übernutzungen der Wasserressourcen verstärkt (Khelifa et al. 2021; Zahn & Burbach 2023; Vicente-Serrano et al. 2024). Wärmeempfindliche Arten zählen jedenfalls zu den „Verlierern“ des Klimawandels (De Knijf et al. 2011; Fliedner-Kalies & Fliedner 2011; Termaat et al. 2019; Bowler et al. 2022; Neff et al. 2022; Olsen et al. 2022; Olthoff & Ikemeyer 2024).

In der vorliegenden Arbeit werden Beispiele aus libellenkundlichen Projekten aus Ostösterreich präsentiert, die klimawandel-bedingte Auswirkungen veranschaulichen. Im Vordergrund stehen dabei die Aspekte Arealerweiterung, Phänologie, klineale Veränderungen von Farbmorphen sowie Habitatverfügbarkeit. Folgen auf die Methodik libellenkundlicher Erhebungen und die angewandte odonatologische Forschung werden diskutiert.

Methoden

Aus einer Mehrzahl von veröffentlichten, einzelnen unveröffentlichten Untersuchungen sowie unpublizierten Daten und Beobachtungen wurden im vorliegenden Beitrag auf den Klimawandel zurückführbare Auswirkungen auf die Libellenfauna zusammengefasst und diskutiert. Die Arbeiten wurden schwerpunktmäßig in Gebieten Niederösterreichs und der Steiermark durchgeführt, die der aquatischen Bioregion Östliche Flach- und Hügelländer zuzurechnen sind (Wimmer et al. 2012). Daten zur Verbreitung stammen aus dem in Erstellung befindlichen, neuen „Libellenatlas für Österreich“ (Holzinger et al. in Vorb.) sowie aus Studien aus der Bioregion Bayerisch-Österreichisches Alpenvorland in Oberösterreich.

Ergebnisse und Diskussion

Arealerweiterung

Crocothemis erythraea (Brullé, 1832) (Abb. 1) wurde zu einer ikonischen Symbolart für klimawandelbedingte Faunenverschiebung (Sánchez-Guillén & Ott 2018) und „schaffte es“ auf die Titelseiten entsprechender Fachbücher (z. B. Essl & Rabitsch 2013). Doch es sind große Anteile der Libellenfauna weltweit, bei denen Veränderungen des Verbreitungsgebiets festzustellen sind. Deutlich mehr als die Hälfte der in Europa vorkommenden

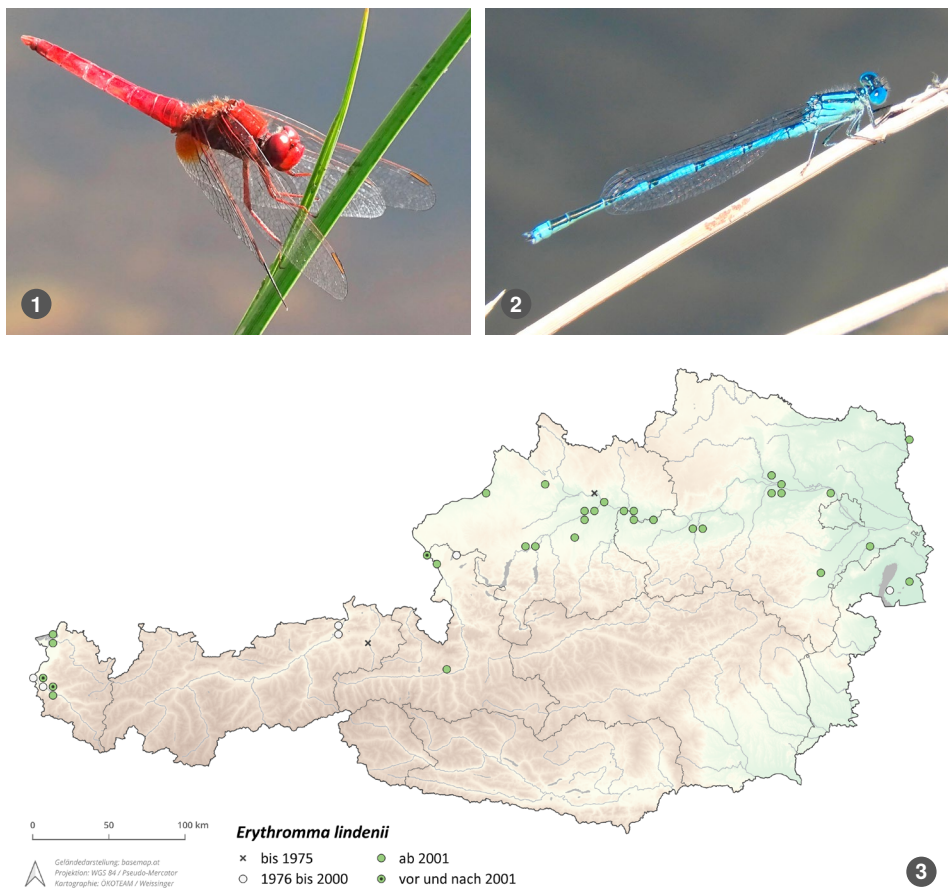


Abb. 1: Ein Männchen von *Crocothemis erythraea*, Pöllau (Ost-Steiermark), 16-07-2021, Foto: A. Chovanec. | **Fig. 1:** A male *Crocothemis erythraea*, Pöllau (Eastern Styria, Austria), 16-07-2021, Photo: A. Chovanec.

Abb. 2: Ein Männchen von *Erythromma lindenii* an der Krems (Oberösterreich), 06-07-2019, Foto: A. Chovanec. | **Fig. 2:** A male *Erythromma lindenii* at the River Krems (Upper Austria), 06-07-2019, Photo: A. Chovanec.

Abb. 3: Verbreitung von *Erythromma lindenii* in Österreich (Karte: Ökoteam). | **Fig. 3:** Distribution of *Erythromma lindenii* in Austria (Map: Ökoteam).

Libellenarten erweiterten als Reaktion auf klimawandelbedingte Temperaturerhöhungen in den vergangenen Jahrzehnten ihr Areal (Termaat et al. 2019). Die Ausbreitungskapazität von Kleinlibellen wird von Góral (2024) diskutiert.

Im Rahmen dieses Beitrages wird beispielhaft auf die Veränderung der Fundsituation von *Erythromma lindenii* (Selys, 1840) (Abb. 2) in Österreich eingegangen (Chovanec et al. in Vorb.). In Europa ist die Art insbesondere im Westen und Süden verbreitet, von wo sie seit

den 1990er Jahren ihr Verbreitungsgebiet deutlich in nördlicher und nordöstlicher Richtung vergrößert hat (Holuša 2023). Diese Arealerweiterung spiegelt sich auch in der Fundsituation in Österreich wider. Die Art, damals noch *Cercion lindenii*, wurde 1965 erstmals für Österreich in Oberösterreich nachgewiesen (Theischinger 1966). Bis zum Jahr 2000 lagen die meisten Fundorte allerdings im Westen Österreichs. Ab dem Beginn des 21. Jahrhunderts verlagerte sich der Schwerpunkt der Nachweise nach Ober- und Niederösterreich (Abb. 3). Das bisher individuenreichste Vorkommen wurde im Jahr 2019 an der Krems in Oberösterreich nachgewiesen (Chovanec 2020). *Erythromma lindenii* kommt vor allem an größeren stehenden und langsam fließenden Gewässern in thermisch begünstigten Lagen vor. Den besiedelten Gewässern gemein sind ausgedehnte Bestände von aufschwimmender Unterwasservegetation.

Veränderung von Farbmorphen

Innerhalb der Anisoptera ist Wachsberiefung insbesondere bei den Libellulidae verbreitet. Das Ausmaß von wachsartigem Überzug kann dabei stark variieren und von der Verbreitung der Art abhängen, wobei heiße Areale bewohnende Populationen tendenziell stärkere Bereifungen ausprägen (Garrison 1976). Sie tritt vorwiegend bei geschlechtsreifen Männchen und fallweise bei alten Weibchen auf und spielt – durch Reflexion von UV-Strahlung – eine Rolle bei der intra- und interspezifischen Kommunikation sowie – durch die Reflexion solarer Strahlung – bei der Thermoregulation (Futahashi 2020; Chovanec 2021a). In Mitteleuropa kommen vier Arten der zu den Libellulidae gehörenden Gattung *Orthetrum* vor: *Orthetrum albistylum* (Selys, 1848), *O. brunneum* (Fonscolombe, 1837), *O. cancellatum* (Linnaeus, 1758) und *O. coerulescens* (Fabricius, 1798). Bei den geschlechtsreifen Männchen dieser vier Spezies ist das Abdomen in artspezifischer Weise stets bereift. Starke Bereifung des Thorax zeigt sich ausschließlich bei reifen Männchen von *O. brunneum* im gesamten Verbreitungsgebiet regelmäßig und ist eines der Erkennungsmerkmale dieser Art. Der Thorax von *O. cancellatum* und *O. coerulescens* ist in Mitteleuropa in der Regel braun (Abb. 4, 5) und kann bei älteren Männchen eine leichte Bereifung aufweisen. Im südlichen Areal kommen Männchen beider Arten vor, deren Thorax stark bereift ist und hellblau erscheint.

Seit dem Jahr 2016 werden in Osten Österreichs vermehrt Männchen von *O. cancellatum* (Abb. 6) und *O. coerulescens* mit sehr stark bereiftem Thorax gesichtet. Das in Abb. 7 dargestellte Männchen von *O. coerulescens* ist nicht mehr anhand der Thoraxfärbung, sondern ausschließlich anhand der Flügeladerung eindeutig als solches zu determinieren. Die diesbezüglichen Funde erfolgten in Niederösterreich in den Bezirken Mödling (beide Arten; Chovanec 2021a, b) und Wr. Neustadt (*O. cancellatum*) sowie in der Steiermark im Bezirk Hartberg-Fürstenfeld (*O. cancellatum*; Chovanec 2024a).

Corbet (1999) hob hervor, dass insbesondere die Bereifung des Thorax thermoregulatorische Funktion hat, da das Abdomen besser durch verhaltensgesteuerte Thermoregulation vor Überhitzung geschützt werden kann (z. B. Wildermuth et al. 2018): Bei der Obeliskenhaltung beispielsweise wird der Hinterleib direkt in Richtung Sonne ausgerichtet, um so die Fläche der von der Wärmestrahlung erfassten Körperoberfläche zu minimieren. Es ist daher wahrscheinlich, dass Populationen der Art mit stärkerer Wachsberiefung des Thorax auf die klimawandelbedingt steigenden Temperaturen und die erhöhte UV-Strahlung in Mitteleuropa (Lorenz et al. 2024) reagieren. Zeuss et al. (2014) belegten, dass die Ausbreitung



Abb. 4: Ein Männchen von *Orthetrum cancellatum* mit braunem Thorax, Matzensdorf (Niederösterreich), 14-06-2021, Foto: A. Chovanec. | **Fig. 4:** A male *Orthetrum cancellatum* with a brown thorax, Matzensdorf (Lower Austria), 14-06-2021, Photo: A. Chovanec.

Abb. 5: Ein Männchen von *Orthetrum coerulescens* mit braunem Thorax, Maria Enzersdorf (Niederösterreich), 27-06-2019, Foto: A. Chovanec. | **Fig. 5:** A male *Orthetrum coerulescens* with a brown thorax, Maria Enzersdorf (Lower Austria), 27-06-2019, Photo: A. Chovanec.

Abb. 6: Ein Männchen von *Orthetrum cancellatum* mit außergewöhnlich stark bereiftem Thorax, Maria Enzersdorf (Niederösterreich), 31-07-2016, Foto: A. Chovanec. | **Fig. 6:** Strong thoracic pruinoscence in a male of *Orthetrum cancellatum*, Maria Enzersdorf (Lower Austria), 31-07-2016, Photo: A. Chovanec.

Abb. 7: Ein Männchen von *Orthetrum coerulescens* mit sehr starker Thoraxbereifung, Maria Enzersdorf (Niederösterreich), 07-07-2019, Foto: A. Chovanec. | **Fig. 7:** A male *Orthetrum coerulescens* with totally pruinose thorax, Maria Enzersdorf (Lower Austria), 07-07-2019, Photo: A. Chovanec.

hell gefärbter Arten durch klimawandelbedingte Temperaturerhöhungen gefördert wird (siehe auch Acquah-Lamprey et al. 2020). Ebenso haben Arten Vorteile, die durch eine entsprechende phänotypische Plastizität in der Lage sind, mit hellen Varianten auf die klimatischen Veränderungen zu reagieren. Der bereifte Thorax erlaubt den Männchen beider Arten, auch bei großer Hitze und Sonneneinstrahlung länger die besonnten Territorien zu besetzen (Chovanec 2021a, b). Inzwischen werden derartige Veränderungen der Bereifung von *O. coerulescens* auch im Norden Deutschlands nachgewiesen (Fahrenholz 2025).

Nachweise eines androchromen, roten Weibchens von *Sympetrum sanguineum* und von Männchen derselben Art mit rotem Thorax wurden von Chovanec (2024b) in Mödling (Niederösterreich) dokumentiert. Möglicherweise sind auch diese phänotypischen Variationen mit der Veränderung klimatischer Faktoren in Verbindung zu bringen. Wie Sternberg (1995) in Versuchen bei Aeshniden feststellen konnte, können erhöhte Umgebungstemperaturen die Ausprägung androchromer Weibchen begünstigen. Entsprechende Beobachtungen von ihm im Freiland bestätigten damals diese Beobachtungen. Futahashi (2016, 2017) zeigte anhand der in Asien auftretenden Spezies *Crocothemis servilia* (Drury, 1773), *Sympetrum darwinianum* (Selys, 1883) und *S. frequens* (Selys, 1883), dass die Rotfärbung adulter Männchen einen Schutz gegen oxidativen Stress bei UV-Strahlung bietet. Der Farb-Polyorphismus bei den Weibchen der Kleinlibelle *Megalagrion calliphya* (McLachlan, 1883) auf Hawaii äußert sich höhenabhängig: Beide Geschlechter der Art sind in größeren Höhen rot gefärbt. In mittleren Höhen sind sowohl androchrome, rote als auch gynochrome, grüne Weibchen zu finden. In tiefen Lagen sind die Weibchen gynochrom. Auch Cooper (2010) brachte dies mit der antioxidativen Eigenschaft roter Pigmentierung in Verbindung, die in größeren Höhen vor Schäden durch UV-Strahlung schützt.

Phänologie

Insbesondere durch libellenkundliche Studien, die Aussagen über längere Zeiträume erlauben, werden klimawandel-bedingte Effekte auf Odonata klar veranschaulicht (Willigalla 2007; Wildermuth 2008, 2010; Suhling et al. 2009). Künstliche Kleingewässer im Wienerwald in Mödling (Niederösterreich) waren sowohl im Jahr 1996 als auch im Jahr 2024 Gegenstand detaillierter libellenkundlicher Untersuchungen (Chovanec 1998, 2024c, 2025). Die hohe Anzahl von Begehungen (1996: 26, 2024: 32) erlaubte unter anderem einen Vergleich der Flugzeiten jener Arten, die in beiden Jahren in bodenständigen Populationen mit langer Präsenz am Standort auftraten.

Tabelle 1 ist zu entnehmen, dass die Emergenzzeiten bei sieben der acht dargestellten Arten im Jahr 2024 früher als im Jahr 1996 begannen. Bei *Pyrrhosoma nymphula* betrug der Unterschied einen Monat. Bei den beiden am frühesten emergierenden Spezies *P. nymphula* und *Libellula depressa* sowie bei *Coenagrion puella* endete die Flugzeit am Standort im Jahr 2024 früher, bei *Sympetrum sanguineum* endete sie in der gleichen Dekade wie 1996, bei drei Arten, *Libellula quadrimaculata*, *Anax imperator* und *Aeshna cyanea*, dauerte sie im Jahr 2024 länger, bei letzterer betrug die Differenz zwei Dekaden. Die Präsenz von *Sympetrum striolatum* endete am Untersuchungsort zwar bereits in der ersten November-Dekade 2024. Am Eichkogel wurden in einer Entfernung von 1 km zum Untersuchungsort allerdings noch am 16.11.2024 Individuen der Art gesichtet. Mit Anfang November waren die untersuchten Gewässer im Wienerwald allerdings kaum mehr besonnt, weshalb die Flugzeit von *S. striolatum* dort früher endete.

Frühlingsarten, wie *P. nymphula* und *L. depressa*, überwintern in der Regel im letzten Larvenstadium F-0, was eine weitgehend synchronisierte Emergenz bedingt (Corbet 1999). Erhöhte Temperaturen im Frühling haben eine frühere Imaginalhäutung zur Folge; aufgrund der komprimierten Emergenzperiode bleibt die zeitlich vorverschobene Flugzeit allerdings etwa gleichlang (siehe auch Hassall et al. 2007; Dingemanse & Kalkman 2008; Richter et al. 2008; Woods & McGarvey 2023). Bei Sommer- und Herbstarten lassen sich nicht nur

Tab. 1: Flugzeiten ausgewählter Libellenarten an künstlichen Kleingewässern im Wienerwald; 1, 2, 3: Monatsdekaden. | Tab. 1: Flight periods of selected Odonata at small artificial ponds situated in the Wienerwald; 1, 2, 3: Decades of the month.

		April			Mai			Juni			Juli			August			September			Oktober			November		
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
<i>Pyrrhosoma nymphula</i> (Sulzer, 1776)	2024																								
	1996																								
<i>Libellula depressa</i> Linnaeus, 1758	2024																								
	1996																								
<i>Libellula quadrimaculata</i> Linnaeus, 1758	2024																								
	1996																								
<i>Coenagrion puella</i> (Linnaeus, 1758)	2024																								
	1996																								
<i>Anax imperator</i> Leach, 1815	2024																								
	1996																								
<i>Sympetrum sanguineum</i> (Müller, 1764)	2024																								
	1996																								
<i>Aeshna cyanea</i> (Müller, 1764)	2024																								
	1996																								
<i>Sympetrum striolatum</i> (Charpentier, 1840)	2024																								
	1996																								

ein früherer Start der Emergenzperiode, sondern auch eine Verlängerung der Flugdauer feststellen. Dies wird auch von Lohr (2016) bestätigt (siehe z. B. auch Patton & Benson 2023). Bei Sommer- und Herbstarten führen erhöhte Temperaturen möglicherweise zu einem verstärkten „cohort splitting“ innerhalb der Larvenpopulationen, zu einer Verlängerung der Emergenzperiode und damit auch der Flug- und Reproduktionsperiode (siehe dazu u. a. auch Wildermuth 1994; Corbet 1999). So ist zu erklären, dass bei *L. quadrimaculata*, *A. cyanea* und *A. imperator* die Flugzeit im Jahr 2024 nicht nur früher begann, sondern auch länger dauerte als im Jahr 1996.

Die Verschiebungen des Beginns der Flugzeiten lassen sich auch mit der Periode der Nachweise der höchsten Artenzahlen ableiten. In dieser Zeit sind sowohl „ausklingende“ Frühlingsarten (z. B. *Cordulia aenea*, *L. depressa*, *L. quadrimaculata*), als auch Frühlings-/Früh-sommerarten (z. B. *C. puella*, *A. imperator*) sowie bereits Sommer-/Herbstarten (z. B. *A. cyanea*, *S. striolatum*) am Gewässer anzutreffen. Im Jahr 1996 fiel diese Periode auf den Zeitraum vom 4.7. bis zum 9.8., in dem maximal 13 bzw. 14 Spezies der insgesamt 26 vorkommenden Arten gleichzeitig anzutreffen waren. Im Jahr 2024 waren bereits vom 23.6. bis zum 29.6. die höchsten Zahlen gleichzeitig auftretender Spezies (12 bis 14 von 21) zu verzeichnen.

Im Zusammenhang mit im Jahresverlauf immer früheren Nachweisen sind auch Funde von *Sympetma fusca* ab dem 18.6.2024 im Bezirk Mödling (Niederösterreich) zu nennen (Abb. 8; siehe auch Chovanec 2024c). Wildermuth & Martens (2019) gemäß beginnt die Emergenzzeit dieser Spezies in Mitteleuropa in der ersten Julidekade, die Hauptemergenzzeit erstreckt sich von Ende Juli bis Mitte August (siehe dazu u. a. auch Thomas 2002; Weitzel 2009; Schweighofer 2011; Nicolai 2025).



Abb. 8: Ein sehr junges Weibchen von *Sympecma fusca*, Brunn am Gebirge (Niederösterreich), 18-06-2024, Foto: A. Chovanec. | **Fig. 8:** A very young female of *Sympecma fusca*, Brunn am Gebirge (Lower Austria), 18-06-2024, Photo: A. Chovanec.

Unter der Reifungsdauer wird die Zeitspanne zwischen den Nachweisen der ersten emergierenden und jenen der ersten adulten Tiere am Gewässer verstanden. *Sympetrum striolatum* ist eine Art, die besonders plastisch auf erhöhte Sommertemperaturen reagiert. Die Reifungszeit, die von *S. striolatum* oft kilometerweit vom Gewässer entfernt verbracht wird, dauert in unseren Breiten etwa zwischen drei und sechs Wochen und kann sich in heißen Sommern auch auf acht Wochen ausdehnen. Verlängerte Reifungszeiten sind für die Art im Mittelmeerraum typisch und dienen dort der Überbrückung des trocken-heißen Sommers (Samraoui et al. 1998). Im Jahr 1996 betrug der Zeitabstand zwischen der frühesten Sichtung der Imagines (4.7.) und der ersten Reproduktion (23.7.) am Untersuchungsort knapp drei Wochen. Im Jahr 2024 betrug die Zeitspanne zwischen dem 20.6. und dem 3.8. etwa sieben Wochen (siehe auch Chovanec 2023a).

Meteorologische Extremereignisse

Meteorologische Extremereignisse nehmen in ihrer Intensität und Häufigkeit zu (GeoSphere Austria 2024a) und werden auch als Gefährdungsursachen für Libellen angesehen (De Knijf et al. 2024a, b). In den Jahren 2023/2024 waren in Ostösterreich meteorologische Konstellationen ausgeprägt, die sich allerdings positiv beispielsweise auf die Entwicklung von *Aeshna affinis* Vander Linden, 1820 (Abb. 9) auswirkten. Hier trat die Art vergleichsweise massenhaft auf (Chovanec 2024d). Die univoltine Spezies ist typisch für stehende Gewässer mit stark schwankendem Wasserstand und für periodische Gewässer. Klimawandelbedingt sinken in



Abb. 9: Ein unreifes, unausgefärbtes Männchen von *Aeshna affinis* in Maria Enzersdorf (Niederösterreich), 05-06-2024, Foto: A. Chovanec. | **Fig. 9:** An immature male *Aeshna affinis* in the colour of the prereproductive period in Maria Enzersdorf (Lower Austria), 05-06-2024, Photo: A. Chovanec.

vielen Regionen die Grundwasserstände. Die Situation wird durch Grundwasserentnahmen für Bewässerungszwecke verschärft. Dies hat zur Folge, dass derartige Gewässer nur mehr eingeschränkt entstehen, erhöhte Temperaturen führen außerdem zu ihrem schnellen Austrocknen. *Aeshna affinis* tritt im Frühsommer auch nicht selten als Invasionsgast aus dem Mittelmeergebiet auf. Die etwa 2–3,5 Monate lang dauernde Entwicklung beginnt im Jänner/Februar nach der Eidiapause (Wildermuth & Martens 2019).

Abbildung 10 zeigt die monatlichen Niederschlagsmengen (in mm) für den Zeitraum Juli 2023 bis Juni 2024 verglichen mit den durchschnittlichen Mengen der Referenzperiode 1961–1990. In Abbildung 11 sind die durchschnittlichen Monatstemperaturen in °C basierend auf den Tagesmittelwerten für den gleichen Zeitraum verglichen mit den entsprechenden Werten aus der Referenzperiode 1961–1990 angegeben: Die aktuellen Durchschnittstemperaturen sind in jedem Monat höher als in der Vergleichsperiode. Die Daten stammen von der Klimastation Wien / Hohe Warte (198 m ü. A.; GEOSPHERE AUSTRIA 2024b).

Die Monate Oktober bis Dezember 2023 waren im Raum Wien durch überdurchschnittlich hohe Niederschlagsmengen gekennzeichnet (Summe für diese Monate: 265 mm gegenüber 135 mm für den Referenzzeitraum 1961–1990). Die Fortpflanzungsgewässer der Art waren daher im darauffolgenden Frühjahr entsprechend gut dotiert. Eine zu rasche Austrocknung, begünstigt durch die geringen Niederschläge im Februar 2024 und die hohen

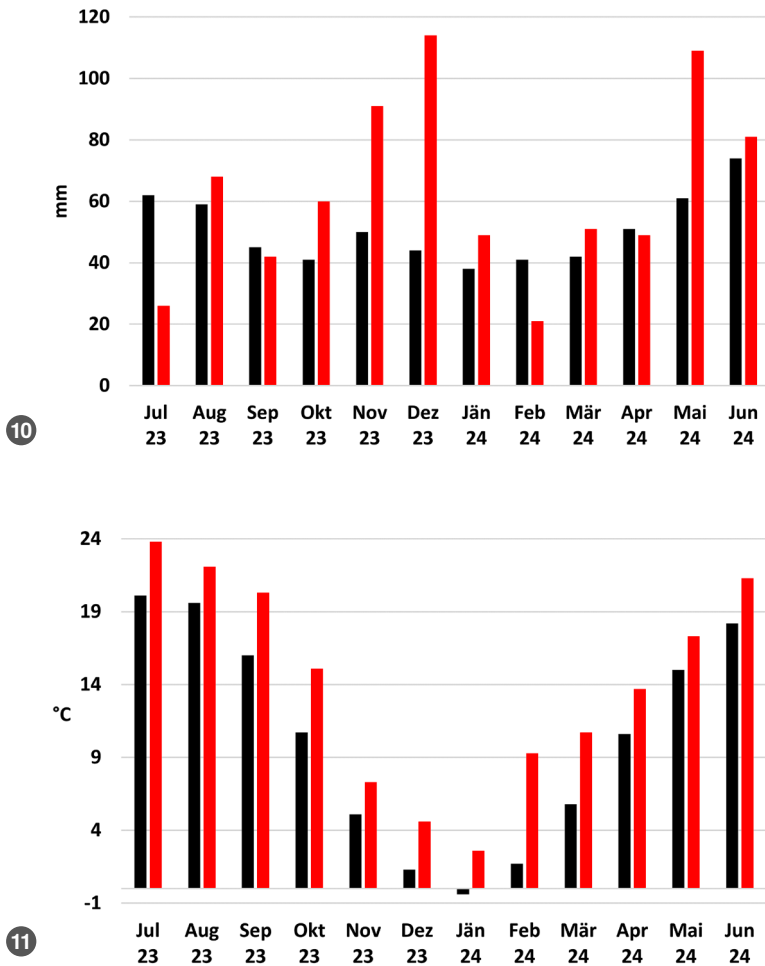


Abb. 10: Monatliche Niederschlagsmengen in mm für den Zeitraum Juli 2023 bis Juni 2024 (rot) verglichen mit den durchschnittlichen Mengen der Referenzperiode 1961–1990 (schwarz). | **Fig. 10:** Monthly precipitation in mm for the period July 2023 – June 2024 (red) compared with the average values of the reference period 1961–1990 (black).

Abb. 11: Durchschnittliche Monatstemperaturen in °C basierend auf den Tagesmittelwerten für den Zeitraum Juli 2023 bis Juni 2024 (rot) verglichen mit der Referenzperiode 1961–1990 (schwarz). | **Fig. 11:** Mean monthly air temperatures in °C based on the daily average values for the period July 2023–June 2024 (red) compared with the reference period 1961–1990 (black).

Temperaturen im Februar und März 2024, wurde möglicherweise durch den regenreichen Mai 2024 verhindert. Die hohen Temperaturen im Frühjahr 2024 förderten die schnelle Entwicklung der Art und förderten die frühe Emergenz. Die in Ostösterreich oft in Verbänden angetroffenen Tiere waren immatur; deshalb handelt es sich bei den Nachweisen nicht um Invasionsgäste (Chovanec 2024d).

Auswirkungen auf die angewandte odonatologische Forschung

Aufgrund ihrer komplexen Lebensraumsprüche spielen Odonata als Indikatoren bei der Bewertung des ökologischen Zustandes von Fließgewässern im Rahmen der wasserwirtschaftlichen Praxis eine große Rolle (z. B. Chovanec 2019, 2020, 2023b; Csar et al. 2024). Ihre Tradition als Zeigergruppe im Naturschutz ist noch viel länger. Aus der Gruppe der aquatischen Wirbellosen stellen Libellen die meisten der in Anhängen der Fauna-Flora-Habitat-Richtlinie (Richtlinie 92/43/EWG) genannten Arten: Von diesen 17 Spezies kommen 11 in Österreich vor. Damit stellen Libellen einen sowohl die Belange des Naturschutzes als auch der Wasserwirtschaft integrierenden „Schirmindikator“ innerhalb des Gewässerschutzes dar.

Die in dem vorliegenden Beitrag erwähnte Art *E. lindenii* ist ein Beispiel für mehrere Spezies, die in Österreich in einzelnen Regionen seit langem nachgewiesen sind, durch ihre Ausbreitung ihr Verbreitungsgebiet in Österreich allerdings deutlich vergrößern. Es stehen auch bereits mehrere „neue“ Arten „vor der Tür“, die mit Sicherheit in naher Zukunft in Österreich gefunden werden. Als Beispiel seien hier *Pantala flavescens* (Fabricius, 1798) und *Trithemis annulata* (Palisot de Beauvois, 1807) erwähnt (Günther 2019; Henseler et al. 2019; Puff et al. 2023). Mit diesen Prozessen sind Auswirkungen auf die Bioindikationsforschung und -praxis verbunden: Die veränderte Verbreitungssituation von Spezies ist bei der Erstellung libellenkundlicher Leitbilder im Rahmen der gewässertyp-spezifischen Bewertung des libellen-ökologischen Zustands von Gewässern zu beachten. Da *E. lindenii* in einzelnen Bundesländern in der Zwischenzeit als etabliert gilt, ist es als Referenzart für die biozönotischen Regionen Meta- und Epipotamal sowie für die Übergangsregion Hyporhithral/Epipotamal zu berücksichtigen; dies gilt insbesondere für die aquatischen Bioregionen Bayerisch-Österreichisches Alpenvorland und Östliche Flach- und Hügelländer (z. B. Chovanec 2020). Eine ähnliche Situation zeichnet sich für *Gomphus pulchellus* Selys, 1840 ab, der ähnliche Ausbreitungstendenzen zeigt (Gros & Chovanec 2018; Chovanec 2023b). Das veränderte Arteninventar für einzelne aquatische Bioregionen sowie für ganz Österreich erfordert auch die Überarbeitung ökologischer Gilden, die ebenfalls zur Festlegung libellenkundlicher Referenzzustände herangezogen werden (Chovanec et al. 2015; Chovanec 2019).

Die Verwendung des Konzepts der biozönotischen Regionen hat sich für die typologische Charakterisierung und Bewertung von Fließgewässern bewährt (z. B. Chovanec 2019, 2020, 2022). Die klimawandelbedingte Erwärmung bewirkt eine Potamalisierung der Gewässer und damit eine Reduktion rhithraler Lebensräume (Hering et al. 2010; Essl & Rabitsch 2013). Damit sind dramatische Auswirkungen auf wärmeempfindliche, rheophile Libellenarten verbunden (Hickling et al. 2005; Outomuro et al. 2010; Fliedner-Kalies & Fliedner 2011; Zahn & Burbach 2023). Eine Adaptierung der gewässertypologischen Charakterisierung der heimischen Fließgewässer, innerhalb der die biozönotische Region einen essenziellen Typisierungsparameter repräsentiert (Wimmer et al. 2012), ist notwendig, um eine den aktuellen Temperaturverhältnissen gerecht werdende Bewertung des ökologischen Zustandes zu gewährleisten. Es wird darüber hinaus zu überprüfen sein, ob auch die klimawandelbedingten Veränderungen der hydrologischen Regime (Wimmer et al. 2012) Auswirkungen auf die rheophile und rheobionte Libellenfauna haben.

Es ist in der libellenkundlichen Fortbildung, in Mitteilungsblättern (z. B. Chovanec 2023c), in der Bestimmungsliteratur sowie im Rahmen von Citizen Science-Programmen verstärkt auf die klinalen Veränderungen der Farbmorphen einzelner Libellenarten hinzuweisen. Da Männchen von *O. cancellatum* und *O. coerulescens* mit stark beireiftem Thorax vergleichsweise leicht mit jenen von *O. brunneum* zu verwechseln sind, ist dies auch bei den entsprechenden Online-Portalen für Fundmeldungen zu berücksichtigen.

Für die Erhebung des imaginalen, aspektbildenden Inventars von Libellenarten an einem Gewässer wird die Durchführung von zumindest fünf bzw. sechs (bei wahrscheinlichem Fund von *Sympecma fusca*) Begehungen empfohlen (Chovanec 2019). Die zeitliche Verschiebung des Auftretens phänologischer Gilden (Schmidt 1985; Chovanec 1998, 2023a) erfordert daher entsprechende Anpassungen der Untersuchungsdesigns. Es ist auch zu berücksichtigen, dass – an entsprechenden Standorten – der Anteil von Arten steigen wird, deren Entwicklung nicht univoltin, sondern bivoltin abläuft (Hoess 2019; Monnerat et al. 2021).

Die Verschiebung von Arealen, der Verlust aquatischer Lebensräume und Veränderungen der Flugzeiten zählen zu den offensichtlichen Auswirkungen des Klimawandels auf die Libellenfauna. Eher „im Verborgenen“ laufen Veränderungen bei zwischenartlichen Interaktionen ab. So führen beispielsweise klimawandelbedingte Vorteile in der Entwicklungsgeschwindigkeit von *S. striolatum* zu Wettbewerbsnachteilen des oft syntop vorkommenden *Sympetrum vulgatum* (Linnaeus, 1758) (Hogreve & Suhling 2022; siehe dazu z. B. auch Stahl & Johansson 2024). Dies mag ein Grund für die negativen Populationstrends dieser Spezies sein, die in der Roten Liste für Europa inzwischen als „gefährdet“ ausgewiesen ist (De Knijf et al. 2024a).

Die immer stärker werdenden Auswirkungen des Klimawandels spiegeln sich auch in der Beurteilung der Gefährdungssituation von Libellen weltweit (Sayer et al. 2025) und in Europa wider. In der Roten Liste für Europa aus dem Jahr 2010 (Kalkman et al. 2010) waren 15 % der 137 beurteilten Arten in einer der Gefährdungskategorien genannt. Unter den Hauptgefährdungsursachen waren als direkt klimarelevante Faktoren „Dürre“ an dritter Stelle und „Lebensraumveränderung durch Klimawandel“ an 14. Stelle genannt. In der überarbeiteten Liste (De Knijf et al. 2024a) sind von 142 beurteilten Arten 20 % in einer Gefährdungskategorie angeführt. Bei den Hauptgefährdungsursachen sind „klimawandelbegründete Dürre“ an zweiter Stelle, „klimawandelbedingte Lebensraumveränderung“ an fünfter und „klimawandelbedingte Temperaturerhöhung“ an zehnter Stelle. Auf diese vergleichsweise rasanten Entwicklungen gilt es, mit zeitnahen Aktualisierungen der Informationen zu Verbreitung und Gefährdung zu reagieren (Hok Yau Tang & Visconti 2020). Für Österreich ist ein aktualisierter „Libellenatlas“ mit neuer Roten Liste in Ausarbeitung (Holzinger et al. in Vorb).

Die oben erwähnte „Rolle“ von Odonata als „Schirmindikatoren“ bedingt, dass – im Lichte der Auswirkungen des Klimawandels – zu Gunsten von Libellen zu ergreifende Schutzmaßnahmen (De Knijf et al. 2024b, Samways 2024) nahezu allen Typen von Oberflächengewässern und Feuchtgebieten und den entsprechenden gewässertyp-spezifischen Lebensgemeinschaften zu Gute kommen.

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Win – Win? Erholung, Tourismus und der Luchs

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In der Naturvermittlung wird zunehmend auf Digitalisierung gesetzt und auch das Vorkommen seltener Wildtierarten wird verstärkt in der Kommunikation mit Besucher und Besucherinnen integriert. Am Beispiel des Luchses (*Lynx lynx*) wurde durch eine Umfrage (n=1.000) mit einem integriertem Choice Experiment untersucht, welche Methoden der Vermittlung in diesem Kontext attraktiv sind. Dabei ergab sich, dass Luchse zu den attraktivsten Tierarten der Alpen gehören und dass alleine die Information zum Vorkommen der Tierart bereits positive Auswirkungen auf das Naturerlebnis der Gäste besitzt. Auch Umwege wegen Schutzmaßnahmen für den Luchs würden keine touristischen Nachteile bedeuten. Die befragten Personen sind nicht an digitalen Lösungen für die Wissensvermittlung über Wildtiere interessiert, sondern vielmehr an geführten Wanderungen oder Wildtierfreigehegen. Eine Zusammenarbeit zwischen Tourismus und Wildtiermanagement könnte im Sinne einer Win-Win-Situation den Luchs in den Mittelpunkt stellen und dadurch eine naturtouristische Entwicklung ermöglichen.

Wanner A, Pröbstl-Haider U, Mostegl N (2026) Recreation, tourism and the lynx

Nature education is increasingly applying digital tools and using rare animal species in communication with tourists. Using the example of the lynx (*Lynx lynx*), a survey with an integrated choice experiment (n=1.000) was conducted to investigate which methods of communication are most attractive in this context. It was recognized that lynx are one of the most attractive species in the Alps and merely providing information about their presence has positive effects on nature-based experiences of tourists. Detours due to protection measures for the lynx do not pose significant disadvantages for tourism. The respondents were less interested in digital solutions for learning about wildlife but were much more interested in guided hikes or wildlife enclosures. Cooperation between tourism and wildlife management could create a win-win situation by focusing on the lynx and enabling the development of nature-based tourism.

Keywords: rural tourism, choice experiment, recreation planning, lynx, nature education.

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Einleitung

Im Zusammenhang mit den Biodiversitätstagen 2025 an der Universität für Bodenkultur in Wien wurde der Einfluss der Digitalisierung auf die Erholungsnutzung und dem Tourismus im Kontext geschützter Arten behandelt. In diesem Zusammenhang zeigte sich, dass Erholungssuchende und Gäste immer mehr digitale Informationen zur Planung und zur Navigation verwenden (Fox 2018; Amerson et al. 2019). Durch die Digitalisierung und der damit einhergehenden Vielfalt unterschiedlicher verwendbarer Formate (wie Fotos, Audio-Dateien, Geoinformationen, Augmented Reality, Videos und Texte), die bei der Führung im Gelände, aber auch bei der Entwicklung touristischer Produkte eingesetzt werden können, ergeben sich jedoch auch neue Möglichkeiten für das Naturraum- und Wildtiermanagement. Tourenportale, Routenplaner, e-Guides, Geocaching, Blogs und Foren, Apps und Websites



Abb. 1: Einfluss der Digitalisierung auf die Besucherlenkung. Mögliche positive Einflüsse sind gelb/hell hervorgehoben, mögliche native Effekte sind orange/dunkel dargestellt. (Pröbstl-Haider 2024 aufbauend auf Job 1993) | **Fig. 1:** Influence of digitalization on visitor management. Possible positive influences in yellow, possible negative effects in orange (Pröbstl-Haider 2024 based on Job 1993)

basieren auf digitalen Informationen und verarbeiten die genannten Formate. Durch diese neuen Optionen und Formate ergeben sich auch Chancen, Wildtiere in die Erlebnisse und Produkte einzubauen (Dagan & Wilkins 2023).

Alleine in Deutschland nutzen rund 65,5 Millionen Menschen (78 % der Bevölkerung) digitale Plattformen. Dabei zeigte sich, dass Plattformen wie Google und Amazon neben sozialen Medien die meistbesuchten Webseiten darstellen (Beisch et al. 2019). Digitale Plattformen für Planung und Navigation werden auch im Freizeitbereich verstärkt angenommen (Schwietering et al. 2024).

Weiterhin werden verschiedene Auswirkungen auf die Besucherlenkung als Folge der Digitalisierung diskutiert. Wie in Abb. 1 dargestellt, können durch die Digitalisierung Schutzgebietskonzepte missachtet werden, wenn die digitale Quelle und Routenplanung keine entsprechenden Informationen enthalten. Die Sozialen Medien haben auch großen Einfluss auf die Entscheidungen der Gäste (Wichman 2024). Probleme können immer dann entstehen, wenn der Gast oder Erholungssuchende die lokalen Informationen mit digitalen Informationen und Empfehlungen abwägt: beachtet man beispielsweise die Sperre eines Weges, wenn man im Smartphone seine Fortführung in geschützte Bereiche und intensive Nutzung erkennen kann?

Lenkungsmaßnahmen, wie Nutzung oder Anreizmittel, können ebenfalls im Konflikt mit digitalen Anreizen und Empfehlungen von anderen digitalen Userinnen und Usern stehen (Mangold et al. 2024). So werden auf unterschiedlichen Portalen auch Touren und Routen

für Wanderungen, Mountainbiken oder zum Klettern von den Nutzern und Nutzerinnen erstellt und öffentlich geteilt, die weder mit Tourismusplanung noch mit dem Naturschutz abgestimmt wurden.

Aber es können sich auch neue Möglichkeiten ergeben, z.B. durch verbesserte Erlebnisqualität oder, neue Optionen für eine Bildung für nachhaltige Entwicklung.

Parallel zur Digitalisierung hat die Pandemie zu einer Veränderung der Relevanz des Naturerlebnisses beigetragen (Pröbstl-Haider & Guggerell 2023). In diesem Zusammenhang wurde deutlich, dass der Aufenthalt in natürlichen Umgebungen die Gesundheit und das Wohlbefinden des Menschen fördert. Allerdings ist noch relativ wenig bekannt, welche Rolle Begegnungen mit Wildtieren oder das Vorhandensein von Wildtieren für das Wohlbefinden spielen (Bell et al. 2018). Forschungsarbeiten in diesem Gebiet lassen einen positiven Einfluss erkennen und empfehlen Möglichkeiten für solche Begegnungen mit Wildtieren und Informationen hierzu zu vermitteln (McIntosh & Wright 2017; Curtin 2005, 2009; Bell et al. 2018).

Dabei gibt es verschiedene Möglichkeiten, Inhalte und Wissen über die Natur und insbesondere Wildtiere zu vermitteln. Dies kann über digitale Medien erfolgen (z.B. durch einen Lehrpfad mit digitalen Informationen durch QR-Code oder einer App), ebenso wie über analoge Angebote in Form einer geführten Wanderung, einem Freigehege oder einem Kinderspielplatz zum Thema Wildtiere mit Informationen, begehbaren Höhlen oder Nestern.

Der vorliegende Beitrag untersucht am Beispiel des Luchses welchen Einfluss das Vorkommen von seltenen Wildtierarten auf den Bergtourismus hat und welche Methoden für die Naturvermittlung in diesem Kontext attraktiv sind.

Dabei gehen wir folgenden Hypothesen nach:

1. Ein Luchsvorkommen hat einen positiven Effekt auf das Naturerlebnis.
2. Der Luchs zählt zu den attraktivsten Tierarten der Alpen.
3. Die Naturvermittlung erfolgt bevorzugt auf digitaler Grundlage.
4. Informationen zum Wildtier Luchs werden durch digitale Medien wie eine App mehrheitlich befürwortet.

Material und Methode

Um die oben genannten Hypothesen beantworten zu können, erfolgte eine repräsentative Befragung von Personen aus Österreich, die regelmäßig Berggebiete für die Erholung und im Urlaub aufsuchen. Die Probandinnen und Probanden wurden u.a. zur Akzeptanz bzw. möglichen Betroffenheit zur Anwesenheit des Luchses befragt. Die Panelbefragung erfolgte zwischen dem 22.10.2023 und dem 24.11.2023. Insgesamt umfasste der Fragebogen die Themen bevorzugte Wildtiere in den Alpen und Präferenzen in der Naturvermittlung. Auch werden Formen der Wissensvermittlung mit Bezug zum Luchs, eine entsprechende touristische Produktentwicklung und Luchsmanagement abgefragt. Nach einer Qualitätsprüfung,

Durch den europaweiten Schutz seltener Arten ist es möglich, dass sich Wildtiere, wie der Luchs, in den Alpen wieder ausbreiten. Ob und inwieweit dies Auswirkungen auf Erholung und Tourismus hat, wird derzeit kritisch diskutiert.

Im Folgenden bitten wir Sie sich sechsmal für eines von zwei Ausflugsgebieten (siehe unten) zu entscheiden. Bitte wählen Sie jedes Mal das Gebiet aus, das Sie unter den angegebenen Bedingungen eher besuchen würden.

	Gebiet A	Gebiet B
Lage zum nächsten Siedlungsgebiet	10 km	30 km
Ausblick	Wenige Aussichtspunkte	Viele Aussichtspunkte
Landschaftscharakter	Wald (80%) , 20% Offenland (Wiesen, Almen und Fels)	Nur im Offenland mit Einzelbäumen , Gehölzen und Latschen
Landwirtschaftliche Nutzung im Gebiet	Keine Nutzung	Mäßige Nutzung (extensive Almweide)
Häufigkeit der Begegnung mit anderen Gruppen pro Stunde	Begegnung mit 1-4 Gruppen von Wanderern oder Mountainbikern	Begegnung mit 11 und mehr Gruppen von Wanderern oder Mountainbikern
Infrastruktur im Gebiet	Bewirtschaftete Berghütte und/oder bewirtschaftete Almen	Bergbahn und Restaurant
Informationen zu Wolfsvorkommen	Es wurden noch nie ein Luchs im Gebiet gesehen.	Es ist bekannt, dass einzelne Luchse das Gebiet queren.
Umweg wegen Schutzmaßnahmen gegen Luchs (Gatterhaltung von Schafen, Herdenschutzhunde)	Kein Umweg erforderlich	Längerer Umweg (60 min.)

Ich wähle   Alternative A  Alternative B  **anderes Ausflugsgebiet**

Abb. 2: Beispiel eines Choice Experiments und den darin enthaltenen Wahlentscheidungen. Jeder Teilnehmende musste 6 Wahlentscheidungen treffen | **Fig. 2:** Example of a choice experiment and the contained decisions. Each respondent made 6 such decisions.

bei der u.a. die Vollständigkeit der Antworten sowie die dafür verwendete Zeit analysiert wurden, umfasste der Datensatz 1.000 Personen.

Die Mensch-Natur-Tier Beziehung wurde auf der Grundlage einer wertebasierten Befragung nach Manfredo et al. (2009) (vgl. auch Hermann et al. 2013) durchgeführt. Zur Unterscheidung in dominante und mutualistische (positive Wechselwirkung) Einstellungen wurde eine Clusteranalyse durchgeführt und mit Hilfe des Cronbach Alpha Werts verifiziert.

Bei den Bewertungsfragen wurde die Antwort „ich weiß nicht“ separat geführt, um klare Antworten in positiver oder negativer Hinsicht zu erhalten.

Wesentlicher Teil des Fragebogens ist auch ein sogenanntes „Choice-Experiment“, bei dem die Befragten zwischen zwei Bergausflügen wählen können. Die zur Auswahl stehenden Bergausflüge unterscheiden sich durch acht Attribute, die in Abb. 2 und Tab. 1 dargestellt sind. Zu den Attributen gehören die Lage zum nächsten Siedlungsgebiet, der Ausblick, der Landschaftscharakter, die landwirtschaftliche Nutzung im Gebiet, die Häufigkeit der Begegnung mit anderen Gruppen pro Stunde, Infrastruktur im Gebiet, Informationen zum Luchsvorkommen und ggf. vorhandene Schutzmaßnahmen. Die Attribute reflektieren somit eine realistische Entscheidung, die Bergwanderer berücksichtigen, wenn sie ein Ausflugsgebiet auswählen.

Tab. 1: Übersicht über die verwendeten Attribute im Choice Experiment | **Tab.1** overview of attributes used in the choice experiment

Attribute	Ebene	Anzahl
Lage zum nächsten Siedlungsgebiet	• 0 km (Streusiedlungen) • 5 km • 10 km • 15 km	4
Ausblick entlang der Strecke	• Wenige Aussichtspunkte • Häufige Aussichtspunkte • Viele Aussichtspunkte • Besonderer Panoramablick	4
Landschaftscharakter	• Überwiegend im Wald (80 %), 20 % Offenland (Wiesen, Almen und Fels) • Überwiegend im Wald (60 %), 40 % Offenland (Wiesen, Almen und Fels) • Überwiegend im Offenland (80 %) (Wiesen, Almen und Fels), 20 % im Wald • Nur im Offenland mit Einzelbäumen, Gehölzgruppen und Latschen	4
Landwirtschaftliche Nutzung im Gebiet	• Keine landwirtschaftliche Nutzung (Schutzgebiet) • Geringe Nutzung (Wiesen, Almen ohne Nutzung oder aufgelassen) • Mäßige Nutzung (extensive Almweide) • Intensive landwirtschaftliche Nutzung (Milchviehhaltung, behirtete Alm)	4
Häufigkeit der Begegnungen mit anderen Gruppen pro Stunde	• Keine Begegnungen • Begegnung mit 1 bis 4 Wanderer- oder Mountainbiker-Gruppen • Begegnung mit 5 bis 10 Wanderer- oder Mountainbiker-Gruppen • Begegnung mit 11 und mehr Wanderer- oder Mountainbiker-Gruppen	4
Infrastruktur im Gebiet	• Einfache Schutzhütten • Bewirtschaftete Berghütte • Bewirtschaftete Alm mit eigenen Milchprodukten • Restaurant • Bergbahn und Restaurant	8 durch Mehrfachnennung
Informationen zu Luchsvorkommen	• Keine Angaben, keine Informationen vorhanden • Es wurden noch nie Luchse im Gebiet gesehen • Es sind wahrscheinlich keine Luchse im Gebiet • Es ist bekannt, dass einzelne Luchse das Gebiet queren • Es leben wahrscheinlich dauerhaft Luchse im Gebiet • Es gibt ein weibliches Tier mit mehreren Jungtieren im Gebiet	8 durch Mehrfachnennung
Umweg wegen Schutzmaßnahmen gegen Luchs	• Kein Umweg erforderlich • Kleiner Umweg: 15 Minuten • Mittlerer Umweg: 30 Minuten • Längerer Umweg: 60 Minuten	4

Das Choice-Experiment basiert auf der Konsumtheorie von Kevin Lancaster (Lancaster 1966). Diese besagt, dass Menschen ihren Nutzen nicht aus dem Konsum von abstrakten Gütern ziehen, sondern aus den Eigenschaften dieser Güter (Attribute). Unterstützt wird

diese Präferenz durch die Random-Utility Theorie (RUT), wonach Menschen immer jenes Gut auswählen, von dem sie den größten Nutzen erwarten (Manski 1977). Die Befragten mussten in sechs Durchgängen das jeweils bevorzugte Ausflugsgebiet auswählen oder sich für „ein anderes Ausflugsgebiet“ (siehe Abb. 2) entscheiden.

Durch die Analyse von insgesamt 6.000 Auswahlentscheidungen ließ sich der relative Einfluss jedes einzelnen Attributes auf das Auswahlverhalten, der sogenannte Teilnutzwert, ermitteln.

Der Fragebogen, insbesondere das Choice-Experiment und dazugehörige Attribute und deren Abstufungen, orientiert sich an vorhandenen Studien zum Wolf (Mostegl & Pröbstl-Haider 2019) und verwendete das gleiche statistische Design der 96 Choice Sets, welche fraktionell-faktoriell mit der Software SAS (SAS Inc. 2013) entwickelt wurden und schlussendlich in das Choice Experiment integriert wurden. Um die Modellgüte sowie Teilnutzwerte des Choice Experiments zu kalkulieren, wurde die Software LatentGOLD 5.1. eingesetzt (Statistical Innovations Inc. 2016). Für die Analyse der restlichen Daten wurde SPSS 21.0 verwendet (IBM SPSS 2012).

Die verwendete Software LatentGOLD 5.1 ermöglichte es außerdem, eine latente Klassenanalyse durchzuführen. Mit der latenten Klassenanalyse lassen sich nicht direkt messbare Eigenschaften, wie z. B. Freizeitverhalten, über direkt messbare Variablen zu Typologien empirisch abbilden. Im vorliegenden Fall wurden die beste Modellgüte bei einem Dreiklassenmodell erreicht. Diese Klassen werden in den Ergebnissen näher beschrieben werden. Aus den Teilnutzwerten der latenten Klassenanalyse wurde ein Excel-basiertes Entscheidungsinstrument (Decision Support System) erstellt (vgl. Abb. 8, 9, 10). Das Instrument ist interaktiv und kann unterschiedliche Szenarien gegenüberstellen und dabei auch anzeigen, wie unterschiedlich die Gruppen darauf reagieren.

Die Einbindung des Luchsvorkommens in die Attribute, die einen Bergausflug bestimmen (vgl. Tab. 1 und Abb. 2) und die Abwägung, z. B. mit störendem Besucheraufkommen, erlaubt Rückschlüsse auf das zu erwartende Verhalten der Gäste und Erholungssuchenden (Pröbstl-Haider et al. 2020). Damit lässt sich die Frage beantworten, ob ein Luchsvorkommen einen Mehrwert für die Erholungssuchenden darstellt, auch wenn der Luchs nicht sichtbar wird.

Ergebnisse

Beschreibung der Probandinnen und Probanden

Das Durchschnittsalter der Befragten war rund 48 Jahre, mit einer Spanne von 18 bis 84 Jahren. Insgesamt nahmen 48,4 % Frauen und 50 % Männer an der Umfrage teil. Eine Person (0,1 %) identifizierte sich als divers, der Rest (1,5 %) bevorzugte es, die Frage nicht zu beantworten. Aus dem ländlichen Raum sowie aus Kleinstädten kommen rund 52 % (34 %; 18 %) und rund 48 % kommen aus Städten und Großstädten. Die Verteilung der Befragten deckt alle Bundesländer Österreichs ab, etwas höhere Anteile nehmen Befragte aus Niederösterreich, Oberösterreich, der Steiermark und Wien ein.

Die Struktur umfasste 19,3 % Einheimische, d.h. Personen, die in einer Bergregion wohnen und regelmäßig entsprechende Bergtouren machen, 32,7 % bezeichneten sich als Urlaubende, die die Berge während ihrer Ferien erkunden und 48 % stuften sich als Tagesgäste ein, die für einen Ausflug in die Berge die alpinen Lebensräume besuchen. Betrachtet man die Dauer der angegebenen Urlaube, dann liegen diese mehrheitlich bei Kurzurlauben mit 2–4 Nächtigungen.

Bei den Urlaubsmotiven dominiert der Wunsch, die Natur zu genießen und sich in der frischen Luft zu bewegen. Auch Ruhe, Erholung und Zeit mit Familie, Freundinnen und Freunden zählen ebenfalls zu den besonders wichtigen Motiven. Die „Beobachtung von Wildtieren in der Natur“ gehört nicht dazu. An der letzten Stelle stehen „Action und Abenteuer erleben“, „Almwirtschaft mit Herstellung von Milchprodukten erleben“ und das Motiv „neue Bekanntschaften zu schließen“.

Das Sample ist auch im Blick auf den Ausbildungsstand ausgeglichen. Etwa 37 % haben eine höherbildende Lehranstalt abgeschlossen, 39 % eine Lehre oder Meisterausbildung und 16 % besitzen eine Fach- oder Hochschulabschluss. Die restlichen 9 % entfallen auf Pflicht- und sonstige Abschlüsse.

Die Befragten wurden auf der Grundlage der Value-Orientations (Manfredo et al. 2009) auch zu ihrer Mensch-Natur-Tierbeziehung befragt. Dadurch ist es möglich herauszufinden, ob und wie stark die Befragten von Domination – d.h. die Probandin oder der Proband vertritt Werte, die eine jagdliche und angemessene Nutzung von Tieren widerspiegeln – oder von Mutualismus – d.h. Werte, die im Blick auf Tiere fürsorgliche Einstellungen widerspiegeln – geprägt sind. Hier zeigte sich, dass bei den Befragten eine mutualistische, fürsorgliche Einstellung deutlich überwiegt.

Attraktivität des Luchses im Vergleich mit anderen Arten

Den Probandinnen und Probanden wurden zum Vergleich Bilder von Luchs, Murmeltier, Adler, Gams, Reh, Fuchs, Alpensalamander, Alpendohle, Bergeidechse und Blindschleiche vorgelegt und nach ihrer Attraktivität gefragt. Dabei zeigte sich, wie in Abb. 3 zu sehen, dass der Luchs zu den sehr attraktiven Tierarten gehört.

Geeignete Formen der Naturvermittlung bezogen auf den Luchs

Wie bereits angesprochen gibt es verschiedene Möglichkeiten, Inhalte und Wissen über die Natur zu vermitteln. Dies kann über digitale Medien erfolgen oder über analoge Angebote in Form einer geführten Wanderung, einem Freigehege oder einem Kinderspielplatz zum Thema Wildtiere. Im Fragebogen wurde die Eignung entsprechender Medien allgemein und bezogen auf den Luchs abgefragt. Die Ergebnisse der allgemeinen Abfrage und der Abfrage bezogen auf den Luchs unterscheiden sich überraschend deutlich (Abb. 4).

Dabei zeigte sich, dass, bezogen auf den Luchs, die digitalen Möglichkeiten (App und digitaler Lehrpfad) deutlich ungünstiger bewertet werden als eine Wanderung mit Informationen, eine geführte Wanderung oder ein Wildtierfreigehege.

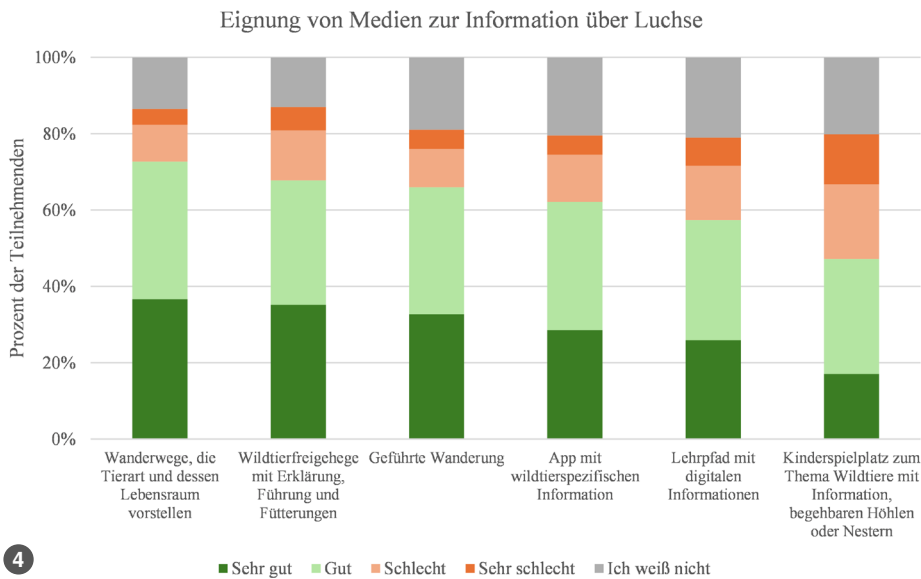
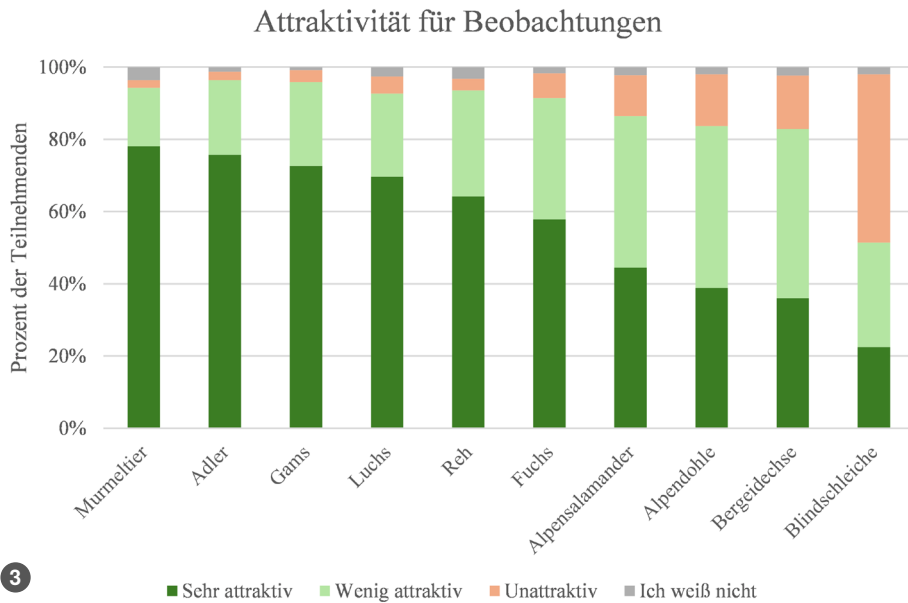


Abb. 3: Murmeltier, Adler, Gams und Luchs gehören zu den besonders attraktiven Arten für eine Beobachtung in der Natur | **Fig. 3:** Marmot, eagle, chamois and lynx are the most attractive species to observe in nature

Abb. 4: Vergleich der Naturvermittlungsangebote mit Blick auf den Luchs | **Fig. 4:** Comparison of nature educational offers for lynx



Abb. 5: Bevorzugte Konzepte für Management und Konfliktlösung | **Fig. 5:** Preferred management concepts for conflict resolution

Abb. 6: Eignung von Institutionen zur Informationsweitergabe | **Fig. 6:** Suitability of institutions for conveying information

Informationen und bevorzugtes Management

Im Hinblick auf Konfliktlösungen und die Regulierung menschlicher Nutzungen und Luchsvorkommen zeigte sich, dass die Mehrheit der Befragten die Alternative bevorzugt, bei der Fachleute den Bestand regelmäßig prüfen und bei Bedarf (Problemen, Verlusten von Schafen und anderen Nutzungen) Konfliktlösungen ausarbeiten. Auch wissenschaftliche Bestandsprüfungen werden für sinnvoll erachtet.

Die Probandinnen und Probanden lehnen intensive Bejagungen und die Verhinderung einer Ausbreitung signifikant ab. Auch die Beschränkung des Luchsvorkommens auf kleinräumig begrenzte Lebensräume wird deutlich abgelehnt. Diese Einstellungen der Befragten sind in Abb. 5 dargestellt.

Auch für die Auskunftsstelle und für Informationseinrichtungen wünschen sich die Befragten wissenschaftliche Grundlagen und Expertinnen und Experten (Abb. 6). Die höchste Zustimmung erhalten Wildbiologinnen und -biologen, also Expertinnen und Experten für den Luchs. Mit deutlichem Abstand folgen erfahrene lokale Jägerinnen und Jäger und die Naturschutzverwaltung. Völlig abgelehnt werden Tourismusinformation, Gemeindeverwaltung und Landwirtschaftskammer als Auskunft-gebende Einrichtung.

Ergebnisse des Choice-Experiments

Segmentierung und Teilnutzenwerte bezogen auf Luchsvorkommen

Die Analyse der Datensätze mit LatentGOLD ergab drei verschiedene Klassen der Erholungssuchenden, die sich in den Motiven, Eigenschaften und Erwartungen unterscheiden: Klasse 1 (59,2 %) umfasst **Tagesausflügler, die als „soziale Bergwandernde“** beschrieben werden können. Sie sind im Durchschnitt etwas jünger als die anderen beiden Klassen. Sie kommen zu höherem Anteil aus urbanem Raum und sind an Naturerlebnisangeboten vor allem in Stadtnähe interessiert. Klasse 1 hat keine besonderen Landschaftspräferenzen, ein Wechsel aus Wald und Offenland wird positiver bewertet. Auch in Fragen der Landnutzung ist diese Klasse weitgehend unentschieden. Nur intensive Landwirtschaft wird klar abgelehnt. Infrastruktur sollte, wie Berghütten, bewirtschaftet sein, ein Bergrestaurant wird allerdings abgelehnt. Sehr wichtig ist ihnen ein schöner Ausblick. Begegnungen mit anderen Erholungssuchenden stellen kein Problem dar.

Klasse 2 (30,9 %) können als **„naturverbundene Bergwandernde“** beschrieben werden. Sie machen überwiegend Urlaub in den Bergen, um Natur zu erleben. Sie sind durch eine starke Werteorientierung bezogen auf den Schutz von Tieren und Natur gekennzeichnet. Diese Klasse hat die meiste Bergerfahrung. Klasse 2 ist an naturnahen Waldlandschaften und wenig an Wiesen und Almen interessiert. Begegnungen wurden abgelehnt, ebenso große Restaurants und Bergbahnen mit Restaurants. Ausblicke und Panoramabereich sind nicht wichtig.

Klasse 3 (9,8 %) wird durch Wochenendurlaubende dominiert. Aufgrund der Präferenzen werden sie nachstehend als **„relaxte Bergwandernde“** charakterisiert. Sie wünschen sich dörfliche Strukturen, suchen Ruhe und Erholung und vermeiden Attraktionen und

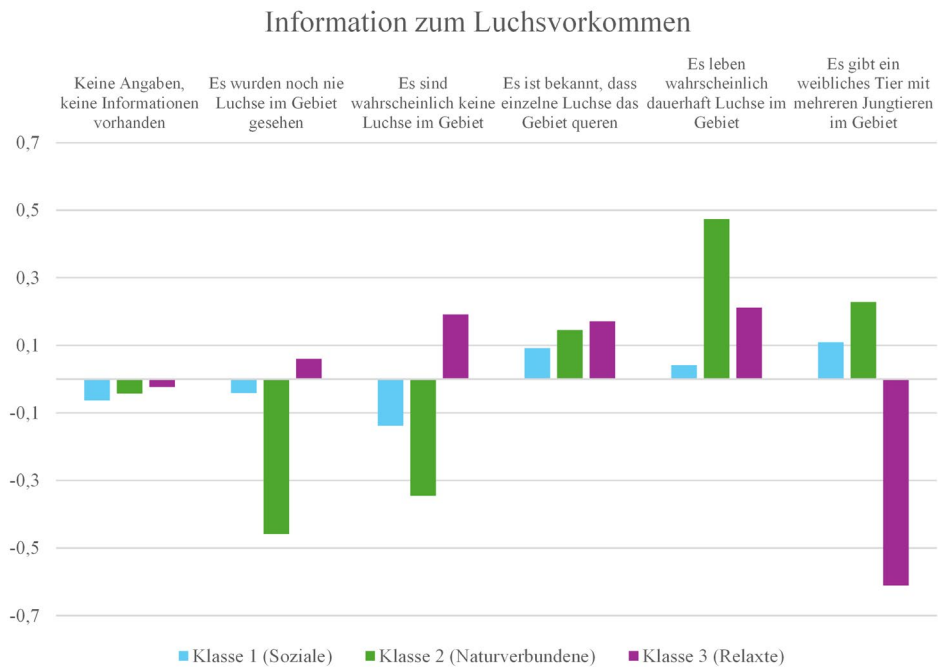


Abb. 7: Teilnutzenwerte im Hinblick auf Informationen zu Luchsvorkommen nach Klassen | **Fig. 7:** Partworth utility for information on lynx by latent class

Überfüllung. Klasse 3 hat ebenfalls geringe landwirtschaftliche Präferenzen. Mäßige Almweide wird bevorzugt, intensive jedoch deutlich abgelehnt. Dies gilt auch für intensive Erschließung und Infrastruktur wie Bergrestaurants und Seilbahnen. Sie ist ebenfalls sensibel im Blick auf Begegnungen mit anderen Erholungssuchenden, allerdings nicht ganz so stark wie Klasse 2.

Im Hinblick auf das Luchsvorkommen ergab die Analyse der Teilnutzenwerte folgende Unterschiede zwischen den Klassen (Abb. 7). Klasse 1 bedauert es, wenn es keine Luchse im Gebiet gibt und reagiert positiv auf jegliche Form der Anwesenheit von Luchsen. Klasse 2 zeigt im Grundsatz dieselbe Reaktion, allerdings in viel stärkerem Maße. Sie bedauern es sehr, wenn keine Luchse vorhanden sind und freuen sich besonders über die Mitteilung „es leben dauerhaft Luchse im Gebiet“. Das Vorkommen verstärkt ihre ohnehin starken naturorientierten Urlaubsmotive. Für die kleine Klasse 3 der Relaxing-orientierten Besucherinnen und Besucher wird es nicht als Nachteil gesehen, wenn noch nie Luchse im Gebiet wahrgenommen wurden. Allerdings ist auch ihr Vorkommen kein Nachteil, sondern wird ebenfalls positiv gewertet. Es gibt nur eine Ausnahme. Mitglieder der Klasse 3 halten offensichtlich weibliche Tiere mit mehreren Jungen fälschlicherweise für eine Bedrohung, wie dies von z.B. Bären bekannt ist. Bei dieser Information sinken die Werte, wie die nachstehende Abb. 7 zeigt, stark ab.

	Gebiet A	Gebiet B
Entfernung zum nächsten Siedlungsgebiet in km	20	20
Ausblick	Häufige Aussichtspunkte	Mit vielen Aussichtspunkten und besonderem Panoramablick
Landschaftscharakter	Überwiegend im Wald (80%), 20% Offenland (Wiesen, Almen und Fels)	Überwiegend im Offenland (80%) (Wiesen, Almen und Fels), 20% im Wald
Landwirtschaftliche Nutzung im Gebiet	Keine landwirtschaftliche Nutzung (Schutzgebiet)	Mäßige Nutzung (extensive Almweide)
Anzahl der Begegnungen mit anderen Gruppen pro Stunde	Keine Begegnungen	Begegnung mit 1-4 Gruppen von Wanderern oder Mountainbikern
Infrastruktur im Gebiet	Einfache Schutzhütten	Bewirtschaftete Alm mit eigenen Milchprodukten
Informationen zu Luchsvorkommen	Keine Angaben, keine Informationen vorhanden	Keine Angaben, keine Informationen vorhanden
Umweg aufgrund von Schutzmaßnahmen gegen Luchse in min	0	0

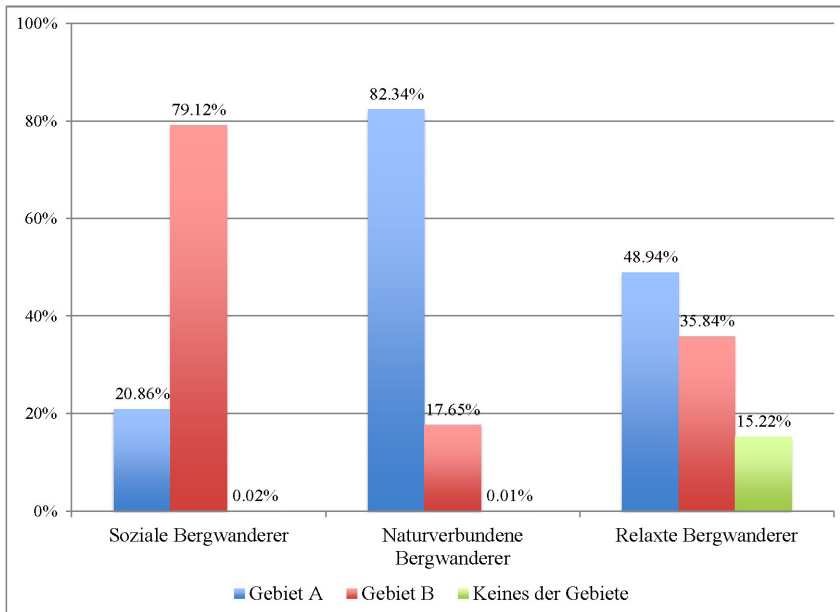


Abb. 8: Landschaftliche Präferenzen ohne Einfluss von Luchsvorkommen. Klasse 1 bevorzugt die offene Landschaft in Gebiet B, die naturverbundenen Bergwanderer bevorzugen Gebiet A mit hohem Waldanteil. | **Fig. 8:** Landscape preference without lynx occurrence information. Class 1 prefers open landscape of B, the nature-loving hikers prefer are A with forests.

	Gebiet A	Gebiet B
Entfernung zum nächsten Siedlungsgebiet in km	20	20
Ausblick	Häufige Aussichtspunkte	Mit vielen Aussichtspunkten und besonderem Panoramablick
Landschaftscharakter	Überwiegend im Wald (80%), 20% Offenland (Wiesen, Almen und Fels)	Überwiegend im Offenland (80%) (Wiesen, Almen und Fels), 20% im Wald
Landwirtschaftliche Nutzung im Gebiet	Keine landwirtschaftliche Nutzung (Schutzgebiet)	Intensive landwirtschaftliche Nutzung (Milchviehhaltung, behirtete Almweide)
Anzahl der Begegnungen mit anderen Gruppen pro Stunde	Keine Begegnungen	Begegnung mit 1-4 Gruppen von Wanderern oder Mountainbikern
Infrastruktur im Gebiet	Einfache Schutzhütten	Bewirtschaftete Alm mit eigenen Milchprodukten
Informationen zu Luchsvorkommen	Es leben wahrscheinlich dauerhaft Luchse im Gebiet	Es wurden noch nie Luchse im Gebiet gesehen
Umweg aufgrund von Schutzmaßnahmen gegen Luchse in min	0	0

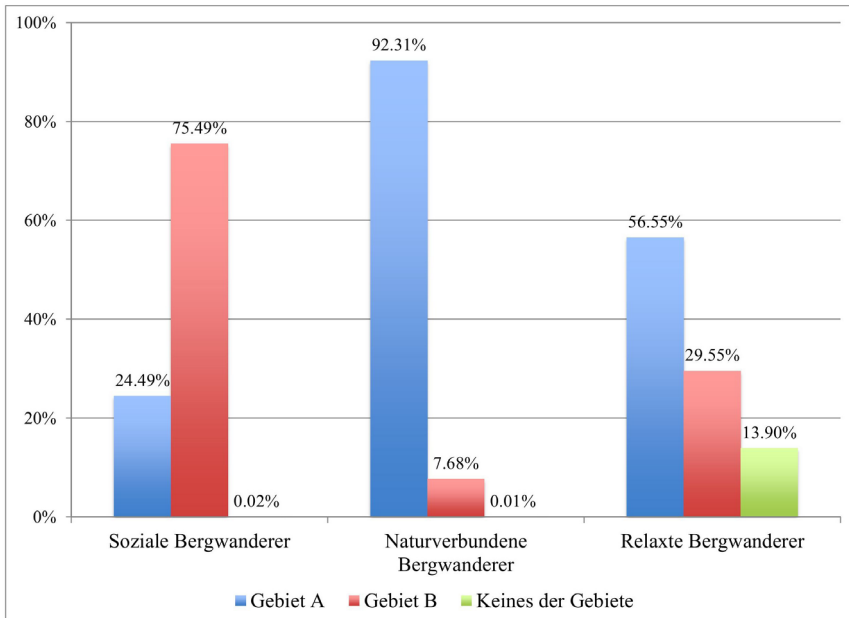


Abb. 9: Bei Vorkommen von Luchs im Gebiet A erhöht dies die Attraktivität für die naturverbundenen Bergwanderer auf über 90 %. Auch für die sozialen Bergwanderer wird dadurch diese Alternative attraktiver. Dies gilt auch für Klasse 3. | **Fig. 9:** If Lynx are present in area A it increases the attractiveness for nature-lovers to over 90 %. It is also more attractive for social and relaxed hikers.

	Gebiet A	Gebiet B
Entfernung zum nächsten Siedlungsgebiet in km	20	20
Ausblick	Häufige Aussichtspunkte	Mit vielen Aussichtspunkten und besonderem Panoramablick
Landschaftscharakter	Überwiegend im Wald (80%), 20% Offenland (Wiesen, Almen und Fels)	Überwiegend im Offenland (80%) (Wiesen, Almen und Fels), 20% im Wald
Landwirtschaftliche Nutzung im Gebiet	Keine landwirtschaftliche Nutzung (Schutzgebiet)	Intensive landwirtschaftliche Nutzung (Milchviehhaltung, behirtete Almweide)
Anzahl der Begegnungen mit anderen Gruppen pro Stunde	Keine Begegnungen	Begegnung mit 1-4 Gruppen von Wanderern oder Mountainbikern
Infrastruktur im Gebiet	Einfache Schutzhütten	Bewirtschaftete Alm mit eigenen Milchprodukten
Informationen zu Luchsvorkommen	Es leben wahrscheinlich dauerhaft Luchse im Gebiet	Es wurden noch nie Luchse im Gebiet gesehen
Umweg aufgrund von Schutzmaßnahmen gegen Luchse in min	30	0

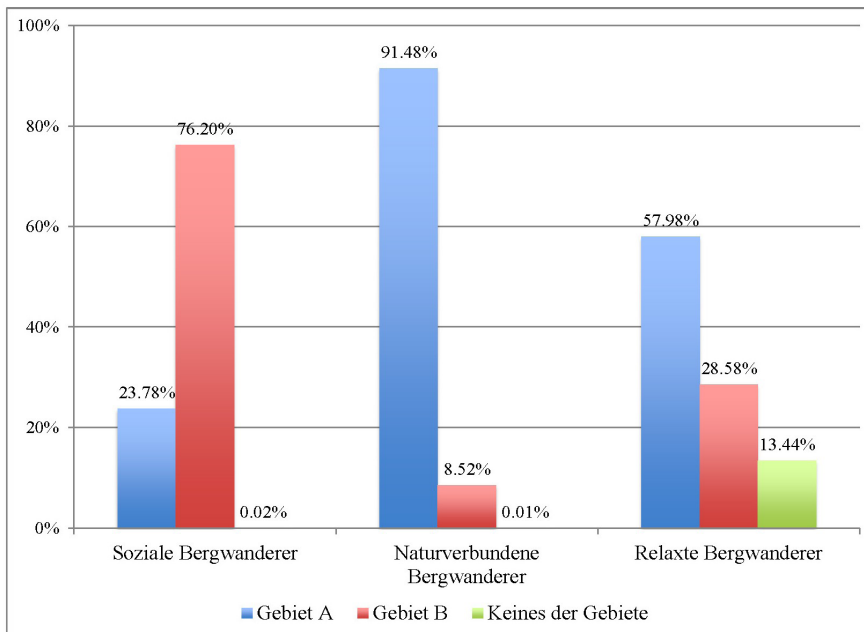


Abb. 10: Ein wegen Schutzmaßnahmen erforderlicher Umweg von 30 Minuten reduziert die veränderte Attraktivität nur unwesentlich. | **Fig. 10:** Introducing a detour of 30 minutes due to protective measures has an insignificant impact on attractiveness.

Einfluss von Luchsvorkommen und Managementmaßnahmen auf die Besuchernachfrage

Auswirkungen durch ein sich ausbreitendes Luchsvorkommen werden vor allem durch Konflikte mit der Landwirtschaft, zum Beispiel durch Verlust einzelner Nutztiere und Beunruhigung, sowie mit der Jägerschaft erwartet (Mostegl et al. 2024). Stellt man ohne Luchsvorkommen zwei Ausflugstypen gegenüber, wobei die eine durch eine bewirtschaftete Alm mit mehr Offenland, und die andere durch eine walddreiche Erholungslandschaft nur mit Schutzhütten als Infrastruktur mit wenig Begegnungen gekennzeichnet ist, zeigt sich, dass die sozialen Bergwanderer die almwirtschaftlich geprägte Landschaft bevorzugt und die naturverbundenen Bergwanderer ebenso wie die Mehrheit von den Relaxten das walddreiche ungestörte Gebiet bevorzugen.

Die nachstehende Abb. 8 zeigt diese Gegenüberstellung, in der nur wenige Begegnungen mit anderen Erholungssuchenden zu erwarten und nur einfache Schutzhütten als Infrastruktur vorhanden sind.

Abb. 9 verdeutlicht Veränderungen in der Präferenz durch die Information zum Vorkommen des Luchs. Hier wird dargestellt, dass im Gebiet (A) dauerhaft Luchse, im anderen Gebiet (B) jedoch keine vorkommen. In diesem Fall wird für alle Erholungssuchenden das Gebiet mit dem Luchsvorkommen attraktiver, besonders jedoch für die naturverbundenen Bergwanderer.

Dies ändert sich selbst bei einem Umweg von 30 Minuten aufgrund von Schutzmaßnahmen gegen Luchse nur sehr unwesentlich. Selbst bei einer Stunde Umweg wird das Gebiet mit dem Luchsvorkommen noch mehrheitlich präferiert.

Im Blick auf Klasse 2, den Naturverbundenen, bedeutet das, dass, obwohl diese Landschaft nicht ihrem Ideal entspricht, der Luchs einen erheblichen Mehrwert für diese naturorientierten Urlaubenden darstellt (siehe Abb. 9).

Diskussion

Attraktivität des Luchses

Wie gezeigt werden konnte gehört der Luchs zu den besonders attraktiven Tierarten der Alpen. Die vorliegende Studie bestätigt damit Untersuchungen von Whiley & Tzanopoulos (2024) und Notaro & Grilli (2021).

Darüber hinaus zeigt sich auch, dass im Vergleich zum Bären und Wolf kein ambivalentes Verhältnis besteht und die Tierart nicht als latente Gefahr empfunden wird. Allerdings scheint, im Hinblick auf eine Junge führende Katze, jedoch Informationsbedarf in dieser Richtung zu bestehen. Eine kleine Gruppe von Befragten (ca. 10 %) hielt diese Situation für gefährdend.

Es stellt sich daher die Frage, ob die gemeinsame Betrachtung und ein entsprechendes Management (vgl. Zentrum für Wolf, Bär und Luchs) sinnvoll ist. Die gemeinsame Betrachtung

leitet sich aus der biologischen Funktion der Beutegreifer ab, aber in der gesellschaftlichen Wahrnehmung werden die Arten sehr unterschiedlich begriffen. Daher sollte auch die Kommunikation zu den Arten sich deutlich unterscheiden. Der Luchs, offenbar mit einem hohen „Sympathievorschuss“ ausgestattet, wird dadurch eher den möglichen Problemtieren zugeordnet, in die er auch aufgrund der, im Vergleich zum Bären und Wolf, begrenzten Schäden für die Landwirtschaft und Jagd offensichtlich nicht gehört (Mostegl et al. 2024). Im Gegenteil, auch ökonomisch betrachtet stellt ein Luchsvorkommen aus touristischer Sicht einen Mehrwert dar, der durch eine entsprechende Produktentwicklung adressiert werden kann. Zu den bekannten Beispielen gehört in diesem Zusammenhang der Luchs-Trail, der den Nationalpark Kalkalpen mit dem Nationalpark Gesäuse und dem Wildnisgebiet Dürrenstein-Lassingtal verbindet und in den kommenden Jahren bis in den Naturpark Ötscher-Tormäuer verlängert werden soll oder das Haus der Wildnis in Lunz am See, das 2021 eröffnet wurde und bereits mehr als 30.000 Gäste pro Jahr begrüßen konnte. Entsprechende Luchs-bezogene Angebote sind auch in anderen Tourismusregionen, wie dem Schwarzwald, dem Harz und dem bayerischen Wald, zu finden. Damit bestätigt sich Hypothese 1, die den positiven Effekt eines Luchsvorkommens auf das Naturerlebnis betrifft.

Aufwertung des Naturerlebnisses durch Luchsvorkommen

Die Visualisierungen zum Ergebnis des Choice Experiments führen deutlich vor Augen, dass sich, trotz unterschiedlicher Motive, positive Aussagen zum Luchsvorkommen auch positiv auf eine Gebietsauswahl auswirken. Einschränkungen, z.B. im Blick auf eine angepasste landwirtschaftliche Nutzung, lassen sich nicht ableiten und ergeben sich nicht einmal durch Umwege, die sich aus einem möglichen Luchsmanagement, Zonierungen oder Wegsperrungen ergeben könnten.

Vor allem für naturorientierte Urlauberinnen und Urlauber ist ein Luchsvorkommen ein ganz besonderer Mehrwert, deutlich stärker als die mehr an Ausflügen interessierten und sozial- und Relaxing-orientierten Klassen 1 und 3. Dies legt nahe, dass Luchsvorkommen in die touristische Vermarktung naturnaher Destinationen aufgenommen werden und das Vorkommen des Luchses durch Zusammenarbeit mit der Jagdwirtschaft aktiv gefördert werden sollte.

Neben den aktuell sehr begrenzten Gebieten mit Luchsvorkommen im Nationalpark Kalkalpen oder den Vorkommen an der Tschechischen Grenze könnten somit auch weitere Landschaften, wie die Ötschergräben in Niederösterreich, touristisch vom Vorkommen des Luchses profitieren. Integration und Mitwirkung der Jagd und der Landwirtschaft sind jedoch unabdingbare Voraussetzungen hierfür (Mostegl et al. 2024).

Insgesamt bestätigen die dargestellten Ergebnisse des Choice-Experiments sowohl bei der Darstellung der Teilnutzenwerte, als auch bei der Darstellung der Abwägungsentscheidungen im DSS, die hohe Relevanz des Luchses. Damit wird auch Hypothese 2 zur touristischen Attraktivität des Luchses bestätigt.

Digitale Naturvermittlung und Information

Anders als erwartet und durch die Literatur nahegelegt werden, bezogen auf den Luchs, nicht digitale Naturvermittlung, sondern eher analoge Formen präferiert. Bezogen auf den Luchs sind Wanderwege, die eine Wildtierart und ihren Lebensraum vorstellen, Wildtier-Freigehege und geführte Wanderungen die am meisten präferierten Vorschläge.

Digitale Lösungen und Apps werden weniger gut gereiht. Betrachtet man den Altersdurchschnitt der Befragten, der bei 48 Jahren liegt, dann kann diese Präferenz auch dem Anteil älterer Befragten geschuldet sein, die einen geringeren Bezug zu digitalen Angeboten haben könnten (vgl. Melchior 2023). Darauf würde auch die Tatsache hinweisen, dass der Anteil von Betroffenen, die „Ich weiß nicht“ antworteten, besonders hoch war (durchschnittlich 22 %).

Auch die nachrangige Einstufung von Kinderspielangeboten mit Informationen, begehbaren Höhlen und Verstecken mag den Altersstrukturen geschuldet sein. Allerdings war hier der Anteil der Personen, die das Angebot für gar nicht geeignet hielten, besonders hoch.

Für die Informationsvermittlung wurden digitale Medien (App, Website des zuständigen Ministeriums) als gut geeignet eingestuft. Die Sorge vor Muttertieren mit Jungen wäre in diesem Zusammenhang ein wichtiges zu ergänzendes Thema für die Information und Kommunikation bei Luchsvorkommen.

Die Befragten wünschen sich auch ein expertenbasiertes Management mit Federführung durch Wildbiologinnen und -biologen. Eine Lenkung des Managements durch die regionale Jägerschaft oder die Landwirtschaftskammer erscheint nicht vorstellbar. Damit bestätigt die Studie auch die Ergebnisse aus Befragungen, die mit Blick auf den Wolf durchgeführt wurden (Hackländer 2019; Mostegl & Pröbstl-Haider 2019).

Zusammenfassung

Der Luchs gehört zu den attraktivsten Tieren im Gebirgsraum. Daher erstaunt nicht, dass er auch von den Erholungssuchenden und Gästen überwiegend als Bereicherung bei der Gebietswahl eingestuft wird. Zu beachten ist, dass dies auch dann gilt, wenn man das Tier nicht sieht bzw. selten sehen kann.

Allerdings spielen weitere wichtige Aspekte, wie die natürliche Ausstattung, die Infrastruktur und die Begegnung mit anderen Erholungssuchenden, ebenfalls eine wichtige Rolle. Überraschenderweise werden Nachteile durch Schutzmaßnahmen, wie ein Umweg der Besucherinnen und Besuchern, toleriert.

Die erwartete zunehmende Bedeutung digitaler Vermittlungsformen bestätigte sich mit Bezug auf den Luchs nicht. Offenbar sollte die Vermittlungsform auch dem Themenfeld angemessen sein.

Insgesamt zeigt sich, dass der Luchs ein großes touristisches Potential darstellt, das, unabhängig von der unmittelbaren Sichtbarkeit, wirkt. Die Ergebnisse könnten eine gute

Grundlage für eine regionale Kooperation aus Tourismus und Landnutzung bilden, bei dem die Förderung des Luchses im Mittelpunkt steht. Verluste einzelner Nutztiere könnten durch die erhebliche naturtouristische Aufwertung bei geeigneter Kompensation auch ökonomisch gut aufgefangen werden.

Die touristische Bedeutung könnte dazu beitragen, das andere gesellschaftliche Gruppen dazu beitragen, dass sich die Luchspopulationen in Österreich langsam erholen. Eine Win-Win-Situation erscheint daher möglich.

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Extended Abstract

Biodiversity Austria – International: Die neue Schnittstelle zum Weltbiodiversitätsrat IPBES

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Im Rahmen der Tage der Biodiversität 2025 an der Universität für Bodenkultur Wien fand eine zweieinhalbstündige Session mit dem Titel „Biodiversity Austria – International: Die neue Schnittstelle zum Weltbiodiversitätsrat IPBES“ statt. In diesem Extended Abstract werden der Kontext sowie der Ablauf und Inhalte der Session vorgestellt.

Im Oktober 2024 wurde das Projekt *Biodiversity Austria – International* gestartet. Es wird durch das Bundesministerium für Land- und Forstwirtschaft, Klima- und Umweltschutz, Regionen und Wasserwirtschaft (BMLUK) gefördert und arbeitet im Kontext der „Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services“ (IPBES). Ziel des Projekts ist es, die Handlungsfähigkeit Österreichs im Umgang mit der Biodiversitätskrise zu stärken. Dies soll durch eine verstärkte Mitwirkung österreichischer Expert:innen an IPBES-Prozessen sowie durch eine verbesserte und zielgerichtete Verbreitung der IPBES-Ergebnisse in Österreich erreicht werden. Das Projekt geht auf eine Initiative des Österreichischen Biodiversitätsrats zurück und ist eng mit diesem assoziiert.

Ziel der Veranstaltung war es, die neue österreichische Schnittstelle zum Weltbiodiversitätsrat sowie die Mitwirkungsmöglichkeiten an IPBES-Prozessen den rund 70 Teilnehmer:innen vorzustellen. Darüber hinaus wurde bei der Session ein Einblick in die Arbeitsweise einer verwandten nationalen Schnittstelle, sowie zu einer persönlichen IPBES-Erfahrung gegeben und die Möglichkeiten der Zusammenarbeit mit bestehenden Institutionen in Österreich aufgezeigt.

Wie funktioniert IPBES eigentlich?

Eröffnet wurde die Session von Prof. Dr. Alice Vadrot (Universität Wien), der Leiterin des Projekts, mit einer Begrüßung und einer Einführung zur 2012 gegründeten internationalen Plattform IPBES (Abb. 1). Besondere Aufmerksamkeit lag auf der hohen Bedeutung von IPBES für das globale Verständnis des Zustands der Biodiversität und zu Ökosystemleistungen. Die verfassten Berichte („Assessments“), insbesondere das erste globale IPBES-Assessment, haben zur Gestaltung internationaler Abkommen geführt. Die Verabschiedung der Zusammenfassungen der Berichte „Summary for Policymakers“ (SPM) – durch die IPBES-Mitgliedstaaten wurde als wichtiges Element des „science – policy“ Prozesses hervorgehoben, durch den die Assessments zusätzliche politische Legitimität erhalten. Neben vielfältigen Beteiligungsmöglichkeiten im Assessmentprozess wurde auch der konzeptionelle Rahmen von IPBES betont, der die Pluralität von Wissensformen und Weltanschauungen abbildet, welche aktiv in die Arbeit der Plattform integriert werden.

Im zweiten Teil der Session folgten vier spannende Kurzvorträge, die nachfolgend kurz vorgestellt werden:

Von der deutschen IPBES-Koordinierungsstelle lernen

Dr. Mariam Akhtar-Schuster (Koordinatorin der deutschen IPBES-Koordinierungsstelle, DLR) präsentierte die 2014 gegründete deutsche Schnittstelle, die sie seit Beginn leitet. Ihre Aufgaben reichen von der Koordination der Nominierung von Expert:innen für IPBES-Assessments über die Unterstützung nationaler Politikprozesse, bis hin zur 1:1-Übersetzung der SPMs ins Deutsche, von denen alle deutschsprachigen Länder profitieren. Da sich in der Schweiz und Österreich, in Anlehnung an die deutsche Koordinierungsstelle, ähnliche Strukturen entwickelt haben, werden die deutschen Übersetzungen mittlerweile kollaborativ erstellt. Eine weitere wesentliche Funktion der deutschen Koordinierungsstelle ist die Einbindung von Expert:innen in die Erarbeitung der deutschen Position



Abb. 1: Vortrag von Prof. Dr. Alice Vadrot zur Funktionsweise von IPBES © Max Guresch / BOKU University | **Fig. 1:** Lecture by Prof. Dr. Alice Vadrot on how IPBES works © Max Guresch / BOKU University

bzw. des Feedbacks Deutschlands auf die SPMs. Im Rahmen eines jährlich abgehaltenen Forums bereitet die deutsche Koordinierungsstelle Plenarsitzungen in einem partizipativen Prozess vor und lädt hierzu im Rahmen kleiner Arbeitsgruppen Expert:innen und Stakeholder:innen ein, während des Forums die Entwürfe im Detail zu besprechen und die Ausarbeitung der Regierungsposition Deutschlands zu unterstützen.

IPBES-Fellow werden, lernen und mitgestalten

Dr. Bernd Lenzner (Universität Wien) teilte seine Erfahrungen als IPBES-Experte. Im Zentrum stand seine Tätigkeit als IPBES-Fellow. Er ist dem IPBES-Call zur Bewerbung gefolgt und hat sich dabei explizit als Fellow für das Assessment zu gebietsfremden invasiven Arten beworben. In seinem Vortrag hat Bernd Lenzner unter anderem über den Bewerbungsprozess berichtet. Das Fellows-Programm, welches sich an 'early career experts' richtet, beinhaltet die gleichen Aufgaben wie für Lead-Autoren, bietet aber auch weitere Workshops und eine:n Mentor:in für den Prozess. Die Arbeit als (Fellow-) Autor in einem internationalen Expert:innenteam hat Lenzner als sehr positiv und bereichernd geschildert. Dabei hob er besonders den Einfluss des Assessments und die daraus resultierende wissenschaftliche Reichweite als Nachwuchswissenschaftler hervor.

IPBES für die Umsetzung der österreichischen Biodiversitätsstrategie nutzen

Dr. Stefan Schindler (Umweltbundesamt) beleuchtete den praktischen Nutzen von IPBES-Assessments. Am Beispiel des Ende 2024 veröffentlichten Nexus-Assessments zeigte er, wie sich die Ergebnisse auf den österreichischen Kontext übertragen lassen. Betont wurde hierbei auch die österreichische Biodiversitätsstrategie 2030+ (Stejskal-Tiefenbach et al. 2022), die bereits Maßnahmen wie die effizientere Wassernutzung in der Landwirtschaft oder die Wiederherstellung von Flussauen adressiert, die mit den Empfehlungen des Assessments übereinstimmen. Schindler betonte abschließend, dass IPBES ein Erfolgsmodell für Wissenschaftskommunikation sei, da eine fundierte Botschaft aus der breiten wissenschaftlichen Gemeinschaft auf die politische Welt trifft und hierbei nicht konfrontiert, sondern in den Dialog geht.

Was kann „Biodiversity Austria – International“ leisten?

Mag. Christian Lettner und Simon Fellingner, MA, stellten abschließend das Projekt *Biodiversity Austria – International* vor. In diesem Vortrag wurden die Tätigkeiten und Struktur dieser neuen österreichischen Schnittstelle präsentiert, die sich gut in zwei Säulen unterteilen lassen: Einerseits bemüht sich die Schnittstelle um die Einbindung österreichischer Expert:innen in IPBES-Prozesse – vom Aufruf zur Mitwirkung in Review-Phasen, bis zur Unterstützung bei Bewerbungen als Autor:innen in Assessments. Andererseits werden IPBES-Assessments für die österreichische Ebene aufbereitet. Zentral wurde hier die Erstellung von österreichspezifischen Versionen der Assessments hervorgehoben. Darüber hinaus wurde die enge Zusammenarbeit mit dem für IPBES verantwortlichen BMLUK, beispielsweise bei der Vorbereitung auf Plenarsitzungen, sowie der Austausch mit Kolleg:innen im deutschsprachigen Raum hervorgehoben.

Im Anschluss fand unter der Moderation von Prof. Dr. Alice Vadrot eine Podiumsdiskussion mit allen Vortragenden statt (siehe Abb. 2). Ins Zentrum der Diskussion rückte die Frage, welche Rolle staatliche Interessen und Konflikte zwischen Regierungen im IPBES-Kontext spielen und ob sich diese auf die finalen Dokumente auswirken. Versuchen einzelne Staaten die Wissenschaft bzw. die IPBES-Berichte – welche einen wissenschaftlichen und politischen Konsens abbilden – strategisch zu beeinflussen und wenn ja, wie wird die Wissenschaftlichkeit und Glaubwürdigkeit der Berichte sichergestellt? Viele Teilnehmer:innen der Veranstaltung interessierten sich für die teilweise zermürbenden Verhandlungen der Assessments durch IPBES-Mitgliedstaaten, die in mehreren Präsentationen der Session thematisiert wurden, da IPBES bisher überwiegend als reines Expert:innengremium wahrgenommen wurde. Dementsprechend spitzte sich die Diskussion auf die Frage zu, wie das Spannungsfeld zwischen Wissenschaft und Politik im Kontext der Bewältigung der Biodiversitätskrise ausgestaltet sein muss und welche Rolle in diesem Kontext die Schaffung von anschlussfähigen Begrifflichkeiten und deren weitreichender Einfluss für Wissenschaft und Politikgestaltung haben. Ein zentrales Beispiel für diese Schaffung von Begrifflichkeiten findet sich bereits in den Anfängen von IPBES: Bei seiner Gründung hat IPBES den Fokus auf Ökosystemleistungen gelegt und daher vor allem den



Abb. 2: Podiumsdiskussion © Max Guresch / BOKU University | **Fig. 2:** Panel discussion © Max Guresch / BOKU University

ökonomischen Wert der Natur in den Vordergrund gestellt. Dies wurde jedoch – vor allem von Regierungen des globalen Südens – aufgrund einer Missachtung der intrinsischen Werte der Natur, die in vielen lokalen und indigenen Gemeinschaften verankert sind, stark kritisiert. Als Reaktion begannen kurz nach Einrichtung von IPBES im Jahr 2012 Verhandlungen über den konzeptuellen Rahmen für die Erarbeitung der Assessments, um die Vielfalt unterschiedlicher Weltanschauungen, wissenschaftlicher Disziplinen und Bedeutungen zu berücksichtigen. Dies mündete schließlich in die Einführung des Konzepts “Nature’s Contributions to People”. Die Aushandlung dessen, was Biodiversität bedeutet, welchen Wert sie hat, wie man sie messen und wie man sie erhalten kann, welche Rolle die Wissenschaft dabei spielt, aber auch wie transdisziplinärer Dialog gelebt wird, zeichnet IPBES im Innersten aus. Hierin liegt auch der Mehrwert für Wissenschaftler:innen, die durch aktive Mitarbeit als Autor:in, Fellow oder Gutachter:in neue Blickwinkel im internationalen Kontext erhalten sowie Erfahrungen auf nationaler Ebene weitergeben können. Darüber hinaus haben sie die Möglichkeit, Einblicke in Forschungslücken zu bekommen, die als Inspiration und Anstoß zum Bilden von Netzwerken und für Publikationen dienen können.

Die Session hat durch Erfahrungsberichte aus verschiedenen Perspektiven sowie durch spannende Einblicke zu einem besseren Verständnis von IPBES beigetragen, einer Einrichtung, die weit mehr als ein reines Expert:innengremium darstellt.

Seit den Tagen der Biodiversität wurde das Projekt *Biodiversity Austria – International* weiter vorangetrieben. Die Vernetzung im deutschsprachigen Raum wurde intensiviert, und öffentlichkeitswirksame Veranstaltungen brachten die Assessments einer breiteren Öffentlichkeit näher. Insbesondere die Erstellung der ersten österreichspezifischen Zusammenfassungen, zum Nexus- und Transformative Change Assessment ist hervorzuheben (Fellinger et al. 2025; Ecker et al. 2026). Diese wurden von interdisziplinären und ehrenamtlichen Expert:innenteams verfasst und durch einen breiten Reviewprozess unter Beteiligung von Ministerien und Wissenschaftler:innen gestärkt. Die österreichspezifischen Zusammenfassungen bringen die globalen Berichte mit einem handlungsorientierten Fokus auf die österreichische Ebene, indem sie den österreichspezifischen Kontext darstellen und konkrete Handlungsperspektiven sowie zukunftsgerichtete Pfade aufzeigen. Zukünftig wird sich *Biodiversity Austria – International* weiter für die Mitwirkung von Expert:innen aus Österreich an IPBES-Prozessen engagieren und IPBES-Assessments, beispielsweise das Business & Biodiversity Assessment im Jahr 2026, aufarbeiten. Ziel ist es, die österreichische Schnittstelle langfristig zu etablieren und durch diese zur Brückenbildung zwischen Wissenschaft, Politik und Praxis beizutragen.

Fellinger S, Vadrot A (2026) Biodiversity Austria – International: The new interface to the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES)

As part of the Biodiversity Days 2025 at BOKU University in Vienna, a two-and-a-half-hour session entitled “Biodiversity Austria – International: The new interface to the World Biodiversity Council IPBES” took place. This extended abstract presents the context, schedule, and content of the session.

The *Biodiversity Austria – International* project was launched in October 2024. It is funded by the Federal Ministry of Agriculture and Forestry, Climate and Environmental Protection, Regions and Water Management (BMLUK) and operates within the context of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). The aim of the project is to strengthen Austria’s capacity in dealing with the biodiversity crisis. This is to be achieved through increased participation of Austrian experts in IPBES processes and through improved and targeted dissemination of IPBES results in Austria. The project stems from an initiative of the Austrian Biodiversity Council and is closely associated with it.

The aim of the event was to present the new Austrian IPBES interface and to introduce the approximately 70 participants to the opportunities for participation in IPBES processes. In addition, the session provided insight into the working methods of a related national interface, as well as a personal IPBES experience, and highlighted opportunities for cooperation with existing institutions in Austria.

How does IPBES actually work?

The session was opened by Prof. Dr. Alice Vadrot (University of Vienna), the project leader, with an introduction to IPBES, which was founded in 2012 (Fig.1). Particular attention was paid to the importance of IPBES, as the assessments it has produced, especially the first global assessment, have contributed significantly to understanding the state of biodiversity and ecosystem services, as well as to the formulation of international agreements. The adoption of the Summary for Policymakers (SPM) by IPBES member states was highlighted as an important science-policy-element that gives the assessments additional political legitimacy. In addition to the diverse opportunities for participation in the assessment process, the conceptual framework of IPBES was also emphasized, which reflects the plurality of knowledge forms and worldviews that are actively integrated into the work of the platform.

The second part of the session featured four exciting short presentations, which are briefly described below:

Learning from the German IPBES platform

Dr. Mariam Akhtar-Schuster (Coordinator of the German IPBES platform, DLR) presented the German interface, which was founded in 2014 and which she has headed since its inception. Its tasks range from coordinating the nomination of experts for IPBES assessments and supporting national policy processes to providing 1:1 translations of the SPM into German, which benefits all German-speaking countries. As similar structures have developed in Switzerland and Austria, inspired by the German coordination office, the German translations are produced collaboratively. Another key function of the German coordination office is to involve experts in the development of the German position and Germany's feedback on the SPMs. As part of an annual forum, the German coordination office prepares a participatory process and invites experts and stakeholders to small working groups to discuss the drafts in detail during the forum and support the development of Germany's government position.

Become an IPBES Fellow, learn, and help shape the future

Dr. Bernd Lenzner (University of Vienna) shared his experiences as an IPBES expert. The focus was on his work as an IPBES Fellow. He responded to the IPBES call for applications and explicitly applied to be a Fellow for the assessment on invasive alien species. In his presentation, Bernd Lenzner reported on the application process, among other things. The fellowship program for early-career experts involves the same tasks as for lead authors, but also offers additional workshops and a mentor for the process. Lenzner described his work as a (fellow) author in an international team of experts as very positive and enriching. He particularly emphasized the influence of the assessment and the resulting scientific reach as a young scientist.

Using IPBES for the implementation of the Austrian biodiversity strategy

Dr. Stefan Schindler (Federal Environment Agency) highlighted the practical benefits of IPBES assessments. Using the example of the 2024 Nexus Assessment, he showed how the results can be transferred to the Austrian context. The focus here was on the Austrian Biodiversity Strategy 2030+ (Stejskal-Tiefenbach et al. 2022), which already addresses measures such as more efficient water use in agriculture and the restoration of river floodplains, which are in line with the recommendations of the assessment. Schindler concluded by emphasizing that IPBES is a successful model for science communication, as it conveys a well-founded message from the broad scientific community to the political world, engaging in dialogue rather than confrontation.

What can *Biodiversity Austria – International* achieve?

Mag. Christian Lettner and Simon Fellingner, MA, concluded the presentations by presenting the *Biodiversity Austria – International* project. This presentation outlined the activities and structure of the new Austrian interface, which can be divided into two pillars: On the one hand, efforts are being made to involve Austrian experts in IPBES processes – from calls for participation in review phases to support for applications as

authors in assessments. On the other hand, IPBES assessments are being prepared for the Austrian level. The creation of Austria-specific versions of the assessments was highlighted as a key aspect. In addition, close cooperation with the BMLUK, which is responsible for IPBES, for example in preparing for plenary meetings, and exchanges with colleagues in German-speaking countries were emphasized.

This was followed by a panel discussion with all speakers, moderated by Prof. Dr. Alice Vadrot (see Fig. 2). The discussion focused on the question of what role state interests and conflicts between governments play within IPBES and whether these have an impact on the final documents. Do individual states attempt to strategically influence science or the IPBES reports – which reflect a scientific and political consensus – and, if so, how is the scientific rigor and credibility of the reports ensured? The sometimes grueling negotiations of the assessments by IPBES member states, which were discussed in some of the presentations, were of interest to many participants at the event, as IPBES had been perceived primarily as a pure expert body. Accordingly, the discussion focused on the question of how the tension between science and politics must be resolved in the context of tackling the biodiversity crisis, and what role the creation of compatible terminology and its far-reaching influence on science and policy-making plays in this context. When it was founded, IPBES primarily emphasized the economic value of nature by focusing on ecosystem services, but this was strongly criticized, especially by governments in the Global South, due to a disregard for the intrinsic values of nature that are anchored in many local and indigenous communities. In response, shortly after IPBES was established in 2012, negotiations began on the conceptual framework for developing the assessments, which led to the introduction of the concept of “Nature’s Contributions to People” in order to take into account the diversity of different worldviews, scientific disciplines, and meanings. Negotiating what biodiversity means, what value it has, how it can be measured and preserved, what role science plays in this, but also how transdisciplinary dialogue is practiced, is at the heart of IPBES. This is also where the added value lies for scientists, who, through active participation as authors, fellows, or reviewers, gain insights into research gaps as inspiration, as well as networking and publication opportunities.

Overall, the session contributed to a better understanding of IPBES as more than just a panel of experts and provided exciting insights through experience reports from different perspectives.

Since the Biodiversity Days, the *Biodiversity Austria – International* project has continued to move forward. Networking in German-speaking countries has been intensified, and high-profile events have brought the assessments to a wider audience. Particularly noteworthy is the creation of the first Austria-specific summaries, on the Nexus and Transformative Change Assessments (Fellinger et al. 2025; Ecker et al. 2026). These were written by an interdisciplinary team of voluntary experts and strengthened by a broad review process, including ministries and scientific experts. These summaries bring the global reports with an action-oriented focus to the Austrian level. In the future, *Biodiversity Austria – International* will continue to promote the participation of experts from Austria in IPBES processes such as the Business & Biodiversity Assessment in 2026. The aim is to establish the Austrian interface in the long term and use it to build bridges between science, politics, and practice.

Keywords: Biodiversity Days, IPBES, Biodiversity Austria – International.

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Extended Abstract

Humans-with-Nature-Areas: Konzepte für naturverträgliche Landnutzung

Elfriede Neuhold ^{1*}, Sophia-Marie Horvath ², Andrea Höltl¹,
Katharina Ranjan¹

Im Rahmen der Biodiversitätstage 2025 wurde ein zweieinhalbstündiger Workshop mit dem Titel, „Humans-with-Nature-Areas: Konzepte für naturverträgliche Landnutzung“ durchgeführt. Geleitet wurde er von der Initiatorin Elfriede Neuhold sowie den weiteren Autorinnen. Ziel des Workshops war es, utopische Visionen einer ökologisch, zugleich jedoch modern ausgerichteten, naturverträglichen Nutzung land- und forstwirtschaftlicher Gebiete zu entwickeln und kreativ sichtbar und erfahrbar zu machen. Es sollten Lebensweisen von Menschen in und mit der Landschaft skizziert werden – orientiert an jahrhundertealten Traditionen und erweitert um moderne Aspekte wie digitale Vermarktungsmöglichkeiten.

Als Basis diente das Konzept der „Humans-with-Nature-Areas“, um die Visionen zu konkretisieren und nicht nur auf einer rationalen Ebene, sondern auf weiteren Ebenen der Wahrnehmung begreifbar zu machen. „Humans-with-Nature-Areas“ sind „Gebiete, in denen Menschen naturnah gemeinschaftlich leben und die gemeinsam ökologisch mit Bedachtnahme auf die lokalen Rahmenbedingungen bewirtschaftet werden.“ (Neuhold et al. 2025).

Die Umsetzung soll durch natürliche Bauweisen, geringstmögliche Versiegelung und durch die ökologische extensive Bewirtschaftung von land- und forstwirtschaftlichen Flächen erreicht werden. Es geht darum, dem Bauernsterben entgegenzuwirken, die lokale Lebensmittelversorgung sicherzustellen und – unterstützt durch zivilgesellschaftliche Initiativen – die land- und forstwirtschaftlich genutzten Flächen (weiterhin) einer extensiven und ökologischen Bewirtschaftung durch Kleinbauern*bäuerinnen sowie neue soziale Gemeinschaften zuzuführen. Dafür braucht es neue Formen des Zusammenlebens und -wirtschaftens (vgl. Neuhold et al. 2025).

Insgesamt lässt sich dieses umfassende Konzept in fünf Themengebiete einteilen. Dazu gehören (1) extensive ökologische Land- und Forstwirtschaft, (2) naturverträgliche Gebäude und Infrastrukturen, (3) Güter versus Konsumgüter, (4) soziale Formen des Zusammenlebens sowie (5) alternative Rechtsformen (vgl. Neuhold et al. 2025).

Der am 26.02.2025 durchgeführte Workshop begann nach einer Vorstellung des Konzepts mit Impulsvorträgen zu Future Literacy sowie zu Potentialen und Möglichkeiten von Kunst in der transdisziplinären Forschung (siehe auch Horvath et al. 2025). Anschließend wurden zwei methodische Zugänge den Teilnehmenden angeboten: einerseits die Methode des Schreibens (siehe Abb. 1) und andererseits die Methode des Improvisationstheaters (siehe Abb. 2). Die Literaturgruppe erhielt Schreibimpulse wie assoziatives Schreiben, das Weiterführen einer Geschichte oder die neutrale Erzählung mit Sicht auf dieses Mensch-mit-Natur-Gebiet durch ein Schlüsselloch. Die drei Literaturgruppen griffen den Impuls eines Gedichts von Christian Morgenstern auf. Sie wählten jeweils eines der fünf Themengebiete, diskutierten und inspirierten sich gegenseitig und formulierten ihre Gedanken vor allem in Prosatexten, aber auch in Gedichtform. Unter anderem entstand folgendes Kurzgedicht:

*„Die Stadtlandschaft der Zukunft:
organisch, vernetzt, vielfältig,
gemeinschaftlich, verbunden, kunstvoll,
mit viel Natur, blühend, duftend,
wild = lebendig.“*

Eine der Gruppen fertigte eine grobe Skizze eines organisch angelegten Stadtquartiers an. Alle Teilnehmenden konnten sich gut auf einen gemeinsamen utopischen Schreibprozess einlassen und eine wünschenswerte Zukunft der Mensch-Natur Beziehung entwerfen.



Abb. 1: Literatur-Workshop zur Skizzierung der Mensch-mit-Natur-Gebiete | **Fig. 1:** Literature workshop on sketching Humans-with-nature areas, Foto/photo: Christoph Gruber

Abb. 2: Theater-Workshop | **Fig. 2:** Improv-theatre workshop, Foto/photo: Christoph Gruber

Der Improvisationstheater-Workshop begann mit einer körperlichen Aufwärm- & Lockerungsübung zu Musik, einer Aktivierung der Aufmerksamkeit mithilfe eines Improvisationsspiels und mit einer freien Positionierung im Raum zur Themenauswahl. Die Gruppe entschied aufgrund der mehrheitlichen Präferenz der Teilnehmenden, sich gemeinsam mit dem Thema extensive ökologische Land- und Forstwirtschaft zu befassen. Nach dem stillen, individuellen Brainstorming im Gehen, versammelten sich die Teilnehmenden in der Mitte des Raums am Boden auf Teppichen und begannen mit einer assoziativen Wortsammlung. Diese abstrakten Ideen wurden in einer freien, mimischen/gestischen Gruppen-Positionierung körperlich ausgedrückt und dargestellt. Bei der finalen Reflexion des Improvisationstheaters waren sich die Teilnehmenden einig, dass sie durch die harmonische (reduziert verbale) Entwicklung des Workshops überrascht gewesen waren. Ebenso darüber, dass das Gruppengefühl sehr schnell hergestellt worden war und dass sie dadurch in einer Gemeinschaft verbunden gewesen waren. Als Bilder kamen Erinnerung an die Kindheit am Bauernhof, an Tiere und an das Pflegen von Pflanzen auf.

Insgesamt konnten die Teilnehmenden durch die kreativen Methoden eine emotionale Verbindung zur Idee der “Humans-with-Nature-Areas” aufbauen und beendeten den Workshop mit neuen Bildern, positiven Gefühlen und Gestaltungsideen für eine zukunftsfähige Mensch-Natur-Beziehung.

Neuhold E, Horvath SM, Höltl A, Ranjan K (2026) Humans-with-Nature-Areas: Concepts for nature-friendly land use

As part of the Biodiversity Days 2025, a two-and-a-half-hour workshop entitled ‘Humans-with-Nature-Areas: Concepts for nature-compatible land use’ was held by the initiator Elfriede Neuhold and the other authors. The aim of the workshop was to create a utopian vision and the creative visualization and sensitization of ecological, yet modern, nature-compatible use of agricultural and forestry areas. The aim was to outline variants of people’s lives in and with the given landscape, as they have been cultivated for centuries, and to link them with new modern aspects such as internet use for marketing and sales.

The concept of ‘Humans-with-Nature-Areas’ was used as a basis in order to concretize the vision and make it comprehensible not only on a rational level, but also on other levels of perception. “Humans-with-Nature-Areas” are “*areas in which people live together in close connection with nature and which are managed jointly and ecologically, with careful consideration of the local conditions*” (Neuhold et al. 2025).

This is to be achieved through natural construction methods, minimized sealing and the ecological extensive cultivation of agricultural and forestry land. The aim is to counteract the extinction of farmers, ensure the local food supply and, by strengthening civil society initiatives, to (continue to) use agricultural and forestry land for extensive and ecological cultivation by small farmers and new social communities. This requires new forms of living and working together (cf. Neuhold et al. 2025).

Overall, this comprehensive concept can be divided into five thematic areas. These include (1) extensive ecological agriculture and forestry, (2) nature-friendly buildings and infrastructure, (3) goods versus consumer goods, (4) social forms of coexistence and (5) alternative legal forms (cf. Neuhold et al. 2025).

After an introduction to the concept, the workshop held on 26 February 2025 began with keynote speeches on future literacy and the potential and possibilities of art in transdisciplinary research (Horvath et al. 2025). The participants were offered two options for approaching the topic: on the one hand via the method of writing (see Fig. 1) and on the other via the method of improv theatre (see Fig. 2). The literature group was given some impulses, such as associative writing, the continuation of a story or neutral narration with a view of this Human-with-Nature-Area through a keyhole. The three literature groups took up the impulse of a poem by Christian Morgenstern. They each chose one of the five themes and discussed and inspired each other. Finally, they put their joint thoughts down on paper, several times in the form of prose but also as poems. For example, the following short poem was written:

*'The urban landscape of the future:
organic, networked, diverse,
communal, connected, artistic,
with lots of nature, blooming, fragrant,
wild = alive.'*

One of the groups drew a rough sketch of an organically designed urban neighborhood. All participants were able to get involved in a joint utopian writing process about a desirable future for our relationship between humans and nature.

The improv theatre workshop began with a physical warm-up and relaxation exercise to music, an activation of attention with the help of an improvisation game and a free positioning in the room to select a topic. Based on the majority preference of the participants, the group decided to work together on the topic of extensive ecological agriculture and forestry. After the silent, individual brainstorming session while walking, the participants gathered in the center of the room on carpets and began to collect associative words. These abstract ideas were physically expressed and presented in free, mimic/gestural group positioning. In the final reflection on the improv theatre, the participants agreed that they were surprised by the harmonious (reduced verbal) development of the workshop. They were also surprised that the group feeling had been established very quickly and that they had been connected in a community as a result. Memories of their childhood on the farm, animals and caring for plants came to mind.

Overall, the participants were able to connect emotionally with the idea of "Human-with-Nature-Areas" through the creative methods and ended the workshop with new images, positive feelings and design ideas for the future.

Keywords: socio-ecological transformation, transdisciplinarity, art, nature-friendly land use, ecological agriculture.

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Abstract

Naturvermittlung und das Bewusstsein für Biodiversität bei Kindern

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Die erfolgreiche Erhaltung von Biodiversität setzt voraus, dass sie als wertvoll wahrgenommen wird. Wissenschaftliche Erkenntnisse lassen sich jedoch nur begrenzt direkt in persönliche Einstellungen und Handlungen überführen. Naturvermittlung mit Schulkindern kann hier einen wichtigen Beitrag leisten, da sie Wissensvermittlung mit positiven Naturerfahrungen verbindet und so ein breiteres Bewusstsein für Biodiversität fördert.

In einer Studie mit 368 Schüler:innen im Alter von 10 bis 17 Jahren wurde der Einfluss dreier Naturvermittlungsprogramme auf das Biodiversitätsbewusstsein untersucht. Verglichen wurden Schulworkshops des Sparkling-Science-Projekts *Lebensraum Gründach* sowie die Programme *Naturerlebnistage* und *Erlebnisunterricht Insekten* des Vereins natopia. Erfasst wurden Wahrnehmung, Wissen, Einstellung und Handlungsbereitschaft im Zusammenhang mit Biodiversität. Die Ergebnisse zeigen eine verbesserte Wahrnehmung von Biodiversität nach allen Programmen, während Effekte auf Einstellung, Handlungsbereitschaft und Begriffswissen vom jeweiligen Format und Schwerpunkt abhingen. Zwar bewerteten die Schüler:innen Biodiversität überwiegend positiv, der Begriff wurde jedoch häufig ungenau verwendet und meist mit Artenvielfalt gleichgesetzt. Zudem zeigte sich eine Diskrepanz zwischen positiver Einstellung und tatsächlicher Handlungsbereitschaft.

Die Ergebnisse liefern wertvolle Hinweise für die Weiterentwicklung naturpädagogischer Angebote zur Stärkung des gesellschaftlichen Biodiversitätsbewusstseins. Der Beitrag wurde bei den *Tagen der Biodiversität 2025* präsentiert und ist bereits im Band 161 der *Acta ZooBot Austria* mit dem Schwerpunktthema Umweltbildung publiziert (Albrecht & Rüdissler 2025).

Albrecht K, Rüdissler J (2026) Nature education and biodiversity awareness in children

The successful conservation of biodiversity depends on it being perceived as valuable. However, scientific knowledge can only be translated to a limited extent into personal attitudes and behaviour. Nature-based education with schoolchildren can make an important contribution in this regard, as it combines knowledge transfer with positive experiences in nature and thereby promotes broader awareness of biodiversity.

In a study involving 368 students aged 10 to 17 years, the effects of three nature education programs on biodiversity awareness were investigated. The programs compared were school workshops conducted within the Sparkling Science project *Lebensraum Gründach* (Habitat Green Roof) and the programs *Naturerlebnistage* (Nature Experience Days) and *Erlebnisunterricht Insekten* (Insect Experience Lessons) offered by the association natopia. Biodiversity-related perception, knowledge, attitudes, and willingness to act were assessed. The results indicate an improved perception of biodiversity following all programs, whereas effects on attitudes, willingness to act, and conceptual knowledge depended on the respective format and thematic focus. Although students generally evaluated biodiversity positively, the term was often used imprecisely and was mostly equated with species diversity. Furthermore, a discrepancy was observed between positive attitudes and actual willingness to take action.

These findings provide valuable insights for the further development of environmental education programs aimed at strengthening societal awareness of biodiversity. The contribution was presented at the *Tagen der Biodiversität 2025* (Days of Biodiversity 2025, Vienna) and has already been published in Volume 161 of *Acta ZooBot Austria* with the thematic focus on environmental education (Albrecht & Rüdissler 2025).

Keywords: biological diversity, knowledge, perception, attitude, willingness to act, environmental education.

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Abstract

DivMoSt – Monitoring of species diversity in meadow orchards and development of methods for automated localization of meadow orchards in Austria

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Species-rich habitats such as traditional meadow orchards have declined in recent decades. These extensively managed grasslands with large-crowned fruit trees of various species and significant age heterogeneity provide important habitats for many different species. The project DivMoSt focuses on the following aspects: Biodiversity surveys of indicator species groups and orchard-specific assessments were conducted in 46 characteristic traditional orchard regions distributed across Austria. The collected data provide a solid basis and complement established biodiversity monitoring programs in Austria. Furthermore, the orchard-specific data are of great importance for further analyses, as there is currently no comprehensive geospatial dataset of traditional orchards in Austria. Therefore, another goal was to develop a method to automatically locate traditional orchard meadows in Austria. The method development was based on mapping traditional orchards, spatially explicit expert knowledge about orchard management, and the analysis of geodata, and especially multi-seasonal spectral data from satellite images with high spatial resolution (e.g. PlanetScope Data). The mapping of 46 km² landscape covered with orchard trees provided the solid training data for the spectral classification of the multi-seasonal satellite data. In combination with additional ancillary data, the location of fruit trees can be determined. To address gaps in biodiversity monitoring of orchard meadows, wild bees, butterflies, and grasshoppers were sampled along standardized transects in the 46 orchard areas. Bats were recorded using automatic ultrasound devices and supplementary net captures, while birds were documented through audio recordings and observations. As of the 2024 surveys, 225 wild bee species, 60 butterfly species, 26 grasshopper species, 22 bat species and 111 bird species have been identified, including species of high nature conservation importance such as the Clouded Apollo (*Parnassius mnemosyne*), the Greater Horseshoe Bat (*Rhinolophus ferrumequinum*), and the Eurasian Wren (*Jynx torquilla*). The results will be incorporated into Austria's biodiversity report to help identify potential threats earlier and implement targeted conservation measures. The project DivMoSt is funded by the European Union – NextGenerationEU, Biodiversity Fund of the Federal Ministry of Agriculture and Forestry, Climate and Environmental Protection, Regions and Water Management.

Kratschmer S, Linhart S, Unglaub P, Milchram M, Immitzer M, Holler C, Rosner F, Staples M, Weißmann M, Silhavy-Richter K, Lanner J, Strausz M, Schuller N, Weis I, Schöll EM, Hengsberger E, Suppan F (2026) DivMoSt – Monitoring der Artenvielfalt von charakteristischen Streuobstflächen in ganz Österreich und Methodenentwicklung zur automatisierten Lokalisierung von Streuobstflächen

Artenreiche Lebensräume wie Streuobstwiesen sind in den letzten Jahrzehnten zurückgegangen. Diese extensiv bewirtschafteten Grünlandflächen mit großkronigen Obstbäumen verschiedener Arten und hoher Altersheterogenität bieten wichtige Lebensräume für viele Tierarten. Das Projekt DivMoSt beschäftigt sich mit folgenden Aspekten: Einerseits wurden Biodiversitätserhebungen von Indikatororganismen sowie streuobstbaufachliche Erhebungen in 46 charakteristischen Landschaftsausschnitten mit Streuobstbeständen, verteilt über ganz Österreich, durchgeführt. Die erhobenen Daten stellen eine fundierte

Grundlage dar und stehen für das Monitoring der Flächen zur Verfügung. Darüber hinaus sind die streuobstbaufachlichen Daten von großer Bedeutung für weiterführende Analysen, da es noch keinen flächendeckenden Geodatenatz von Streuobstbeständen in Österreich gibt. Ein weiteres Ziel war es daher, eine Methode zu entwickeln, um Streuobstflächen in Österreich automatisiert zu lokalisieren. Die Methodenentwicklung basierte auf der Kartierung der Streuobstbestände, räumlich explizitem Experten*innenwissen über den Streuobstbau, der Analyse raumbezogener Daten, und speziell multisaisonaler spektraler Daten von Satellitenbildern mit hoher räumlicher Auflösung (z.B. PlanetScope Daten). Die Kartierung von 46 km² mit Streuobstbeständen und Einzelbäumen stellte einen soliden Trainingsdatensatz für die spektrale, multisaisonale Klassifikation von Obstbäumen dar. Durch die Kombination mit weiteren Geodaten (wie z.B. der digitalen Katastralmappe) können die Standorte von Obstbäumen ermittelt werden. Um Lücken im Biodiversitätsmonitoring auf Streuobstwiesen zu schließen, wurden Wildbienen, Tagfalter und Heuschrecken entlang standardisierter Transekte in ausgewählten Streuobstbeständen der 46 Landschaftsausschnitte beprobt. Fledermäuse wurden mit automatischen Ultraschallgeräten sowie ergänzenden Netzfängen, und Vögel durch Audioaufnahmen und Beobachtungen erfasst. Durch die Erhebungen im Jahr 2024 konnten bis jetzt 225 Wildbienen-, 60 Tagfalter-, 26 Heuschrecken-, 22 Fledermaus- und 111 Vogelarten nachgewiesen werden, darunter naturschutzfachlich hochrelevante Arten wie z.B. der Schwarze Apollofalter (*Parnassius mnemosyne*), die Große Hufeisennase (*Rhinolophus ferrumequinum*) oder der Wendehals (*Jynx torquilla*). Die Ergebnisse werden in den österreichischen Biodiversitätsbericht einfließen, um mögliche Bedrohungen früher ersichtlich zu machen und gezielte Schutzmaßnahmen zu setzen. Das Projekt DivMoSt wird finanziert von der Europäischen Union – NextGenerationEU und dem Biodiversitätsfonds des Bundesministeriums für Land- und Forstwirtschaft, Klima- und Umweltschutz, Regionen und Wasserwirtschaft.

Keywords: biodiversity, classification, fruit tree, spatial, spectral monitoring.

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Abstract

Challenges of Integrated Sustainable Development of Ground-Mounted Photovoltaic Systems (BioPV)

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The overarching goal of the project BioPV (<https://biopv.boku.ac.at/>) is to investigate the potential contribution of ground-mounted photovoltaic (PV) systems to two pressing global crises: climate change and biodiversity loss. The project examines technical-economic, social, ecological, and landscape-related conflicts and develops possible solutions. Specifically, we explore (i) potential goal conflicts between biodiversity and PV systems and propose solutions; (ii) which factors influence public acceptance of PV systems among stakeholders and local communities; and (iii) how participatory planning processes supported by visualization techniques can promote public awareness and enable greater involvement in decision-making.

The technical-economic modeling conducted within the project focuses on five overarching criteria: solar radiation, land cover and topography, economic viability, infrastructure, and natural hazard zones. While solar radiation in biosphere parks is generally high, not all open areas are suitable for the installation of PV systems. Initial findings indicate that proximity to existing power infrastructure is especially important for economic reasons, particularly for PV systems smaller than 5 hectares.

Field studies on selected insect groups (wild bees, grasshoppers, butterflies) in existing PV systems and reference areas show a wide range of possible impacts on biodiversity and underscore the need for multi-criteria site selection and tailored management strategies. Interviews and a conjoint study examine social and ecological aspects, as these often hinder the implementation of renewable energy projects.

Since the energy transition relies heavily on local decision-making, there is a significant need for improved conflict management and stakeholder involvement in planning and decision-making processes. By identifying and analyzing potential obstacles and solutions, BioPV offers valuable insights into sustainable energy production while also strengthening the resilience of regional landscapes.

The project is funded by the Earth System Sciences program of the Austrian Academy of Sciences.

Pachinger B, Baumgartinger-Seiringer M, Bittner K, Hainz-Renetzeder C, Klic R, Mikovits C, Plöchl J, Schauppenlehner T, Sposato R, Scherhauser P (2025) Herausforderungen einer integrierten nachhaltigen Entwicklung bei PV-Freiflächenanlagen (BioPV)

Das übergeordnete Ziel des Projektes BioPV (<https://biopv.boku.ac.at/>) ist es, den potenziellen Beitrag von Freiflächen-Photovoltaikanlagen zu zwei außergewöhnlichen aktuellen globalen Krisen zu untersuchen: dem Klimawandel und dem Rückgang der Biodiversität. Das Projekt untersucht technisch-ökonomische, soziale, ökologische und landschaftliche Konflikte und erarbeitet mögliche Lösungen. Insbesondere untersuchen wir (i) mögliche Zielkonflikte zwischen Biodiversität und PV-Systemen und Lösungsvorschläge; (ii) welche Faktoren für die gesellschaftliche Akzeptanz von PV-Systemen bei Interessensgruppen und der lokalen Bevölkerung eine Rolle spielen können und (iii) wie ein partizipativer Planungsprozess unterstützt durch Visualisierungstechniken das öffentliche Bewusstsein und die Möglichkeiten der Mitbestimmung fördern können. Die im Projekt durchgeführten technisch-ökonomischen Modellierung konzentriert sich auf fünf übergeordnete Kriterien: Solare Einstrahlung, Landbedeckung und Topographie,

Wirtschaftlichkeit, Infrastruktur und Naturgefahrenzonen. Während die Sonneneinstrahlung in Biosphärenparks im Allgemeinen hoch ist, eignen sich nicht alle Freiflächen für die Errichtung von PV-Anlagen. Erste Ergebnisse zeigen, dass vor allem die Nähe zu bestehenden Strominfrastrukturen aus wirtschaftlichen Gründen entscheidend ist, insbesondere für PV-Anlagen, die kleiner als 5 ha sind. Felduntersuchungen an ausgewählten Insektengruppen (Wildbienen, Heuschrecken, Tagfalter) in bestehenden PV-Anlagen und Referenzflächen zeigen eine große Bandbreite möglicher Auswirkungen auf die Biodiversität und unterstreichen die Notwendigkeit einer multikriteriellen Standortauswahl sowie angepasster Managementkonzepte. Interviews und eine Conjoint-Studie untersuchen soziale und ökologische Aspekte, da diese häufig die Umsetzung von Projekten im Bereich erneuerbare Energien verhindern. Da die Energiewende von vielen lokalen Entscheidungen abhängt, besteht ein großer Bedarf an besserem Konfliktmanagement und Beteiligung an Planungs- und Entscheidungsprozessen. Durch die Berücksichtigung und Analyse potenzieller Hindernisse und Lösungsmöglichkeiten bietet BioPV wertvolle Erkenntnisse im Bereich der nachhaltigen Energieerzeugung und fördert gleichzeitig die Widerstandsfähigkeit regionaler Landschaften.

Das Projekt wird aus den Mitteln des Earth System Sciences Förderprogramms der Österreichischen Akademie der Wissenschaften finanziert.

Keywords: renewable energy, climate change mitigation, biodiversity conservation.

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Abstract

Wie verändern KI-basierte Anwendungen die Planungspraxis? Jüngste Entwicklungen bei der Erfassung und Verarbeitung von Biodiversitätsdaten und deren Implikationen für den Umgang mit der Biodiversitäts- und Klimakrise

Robin Sandfort¹, Eva Maria Schöll², Jörg Fabian Knufinke², Brady Mattsson², Alexandra Jiricka-Pürer^{3*}

Ziel des interdisziplinären Workshops im Rahmen der Tage der Biodiversität 2025 war es, mit Praktiker*innen (i) den Bedarf an zusätzlichen Biodiversitätsdaten für die Energieraumplanung und (ii) die Rolle der jüngsten Entwicklungen bei der KI-gestützten Erfassung und Analyse von Biodiversitätsdaten zu diskutieren. Die Workshop-Teilnehmer*innen vertraten sowohl die Wissenschaft als auch Beratungsunternehmen und NGOs. Letztlich nahmen 16 Personen an dem Workshop teil.

Als ersten Beitrag hielt Eva Schöll eine Präsentation, die auf Erkenntnissen aus dem EU Horizon Projekt WIMBY („Wind in my backyard“) basierte. Die Präsentation fasste die planerischen Herausforderungen zusammen, die sich aus den vielfältigen Landnutzungsänderungen ergeben, einschließlich offener Fragen für die zusätzliche Daten benötigt werden bzw. wo KI-gesteuerte Ansätze besonders relevant sein könnten, um diese Wissenslücken zu schließen.

Anschließend stellte Robin Sandfort konkrete und praktische Beispiele für die Anwendung dieser neuen Ansätze vor, wobei der Schwerpunkt auf innovativen Methoden der Datenerfassung und -analyse lag. Zu den vorgestellten Fallstudien gehörten das Management von Neophyten, die Charakterisierung des Lebensraumverbundes und die Überwachung der Abundanz von Arten. Im zweiten Teil des Vortrags wurde aufgezeigt, wie die biologische Vielfalt in Zukunft mit Unterstützung von KI besser berücksichtigt und gefördert werden könnte. Ein Schwerpunkt lag dabei auf der Untersuchung der Wirksamkeit automatisierter Ansätze, die eine effizientere Auswertung und Zugänglichkeit der vielfältigen Daten aus dem Biodiversitätsmonitoring ermöglichen. Zur Veranschaulichung wurden Beispiele für technologische Innovationen in der Energieplanung vorgestellt und die Herausforderungen für deren Umsetzung in der Raum- und Umweltplanung aufgezeigt.

Als Input für den interaktiven Teil schlug Alexandra Jiricka-Pürer die Brücke von der bisherigen Berücksichtigung der Biodiversität auf überörtlicher und lokaler (projektspezifischer) Planungsebene hin zu einem Paradigmenwechsel, der durch EU-Politiken wie RED III oder die Taxonomieverordnung eingeleitet wurde, die einerseits bessere Entscheidungsgrundlagen auf überörtlicher (regionaler) Ebene erfordern und gleichzeitig den Fokus weg von Kompensation („No-Net-Loss“) hin zur Förderung der Biodiversität („Net-Gain“) verschieben. Anschließend stellte sie das Planspiel (Schwerpunkt Energieraumplanung) und Beispiele vor, die als Grundlage und Anregung für den interaktiven Workshop-Teil dienten, in dem die Teilnehmer*innen die vorgestellten Ansätze und Technologien einschließlich der Möglichkeiten der Übertragung auf ihren eigenen Arbeitskontext weiter diskutierten.

In zwei Kleingruppen wurden in Folge die aktuellen Entwicklungen von KI-Ansätzen in Zusammenhang mit europäischen Politiken interaktiv diskutiert. Ziel war es, Chancen und Risiken aus unterschiedlichen Perspektiven zu beleuchten, insbesondere im Hinblick auf Anforderungen an Biodiversitätsdaten, die sich aus europäischen Politiken und Vorgaben wie der RED III-Richtlinie, dem Renaturierungsgesetz und der Taxonomie-Verordnung ergeben. Um die Potentiale und Herausforderungen in einem greifbaren Kontext zu diskutieren, wurden den Teilnehmenden der beiden Kleingruppen Landschaftsausschnitte

mit unterschiedlichem Planungsraum (klein- und großräumiger) zur Verfügung gestellt. Mithilfe von vorbereiteten Symbolen hatten die Teilnehmenden die Möglichkeit, auf den Karten zu markieren, inwieweit sie bereits mit bestimmten Datengrundlagen vertraut sind, die unter anderem durch KI-basierte Ansätze erfasst wurden. Ein zentraler Fokus lag darauf, die Möglichkeiten von KI-basierten Anwendungen zu erkunden, um die Vielfalt der Daten in der Biodiversitätsforschung und -überwachung handhabbar, zuverlässig und zugänglich zu machen. Darüber hinaus wurde diskutiert, wie KI-gestützte automatisierte Ansätze genutzt werden können, um bestehende Datenerhebungen zu ergänzen. Ebenso wurden Herausforderungen, die dabei auftreten können, betrachtet. In der Zusammenschau der Kleingruppen wurden abschließend in der Betrachtung beider Planungsebenen Chancen und Risiken zusammengeführt, die sich aus dem Einsatz von KI-basierten Ansätzen ergeben. Dabei wurde unter anderem aufgezeigt, wie die Integration von Biodiversität auf regionaler Planungsebene verbessert und die Erkennung von Konflikten effizienter gestaltet werden kann. Ebenso wurde diskutiert, wie ein Einsatz neuer KI-gestützter Ansätze zur Datengewinnung und -analyse einen Paradigmenwechsel von "No-Net-Loss" zu "Net-Gain" unterstützen könnte. Ein weiterer Schwerpunkt lag auf der Frage, wie sich die Generierung von Basisdaten zur Bewertung von Umweltauswirkungen und Planungsalternativen sowie das Management und Monitoring von Maßnahmen zum Erhalt und zur Förderung der Biodiversität durch den Einsatz von KI verändern könnten. Dabei wurde erörtert, welche Auswirkungen dies auf die Planungsqualität und frühzeitige Erkennung von Konflikten haben könnte.

Die meisten Teilnehmer*innen äußerten sich optimistisch über das Potenzial für die Integration neuer KI-gestützter Ansätze und diskutierten mehrere Ideen, die z. B. mit der Überwachung des Zustands sowie zusätzlichen qualitativen Indikatoren verbunden sind. Die Skepsis bezog sich auf Ressourcen, Rechtssicherheit und Verantwortlichkeiten. Eine zentrale Frage war, wie sich die Generierung von Basisdaten für die Bewertung von Umweltauswirkungen und Planungsalternativen sowie das Management und Monitoring von Maßnahmen zur Erhaltung und Förderung der Biodiversität durch KI verändern könnte. Es wurde diskutiert, welche Auswirkungen dies auf die Planungsqualität und die Konflikterkennung haben könnte. Abschließend diskutierten die Teilnehmer*innen mögliche weitere Kooperationen zwischen Wissenschaft und Praxis hinsichtlich der Qualitätssicherung der KI-Anwendung sowie der ständigen technischen Weiterentwicklung.

Sandfort R, Schöll EM, Knufinke JF, Mattsson B, Jiricka-Pürrier A (2026) How will AI-based applications change planning practice? Recent developments in the collection and processing of biodiversity data and their impact on addressing the biodiversity and climate crisis

The aims of the interdisciplinary workshop were to discuss with practitioners (i) the need for additional biodiversity data to inform spatial energy planning, and (ii) the role of recent developments in AI-supported collection and analysis of biodiversity data. Workshop participants represented both science and consultancies as well as NGOs. In total, 16 people participated in the workshop. As an initial contribution, Eva Schöll gave a presentation based on findings from the EU Horizon project WIMBY ("Wind in my backyard"). The presentation summarized the planning challenges arising from multiple land use changes, including open questions regarding e.g. connectivity that require additional data, and how new AI-driven approaches could be particularly relevant in addressing these knowledge gaps. Subsequently, Robin Sandfort presented concrete and practical examples of applying these new approaches with a focus on innovative methods of data acquisition and analysis. Presented case studies included neophyte management, characterizing habitat connectivity, and monitoring abundance of species. The second part of the presentation demonstrated how biodiversity could be better considered and promoted in the future using AI. A key emphasis was on examining the effectiveness of automated approaches for enabling more efficient evaluation and accessibility of diverse data obtained through biodiversity monitoring. To illustrate this, examples of technological innovations related to energy planning were presented along with the challenges for implementing these in spatial and environmental planning.

As input for the interactive part, Alexandra Jiricka-Pürrier bridged the gap from the previous consideration of biodiversity at supra-local and local (project-specific) planning levels to a paradigm shift initiated by EU policies such as RED III or the Taxonomy

Regulation, which on one hand require better decision-making foundations at the supra-local (regional) level and simultaneously shift the focus away from compensation (“No-Net-Loss”) toward enhancing biodiversity (“Net-Gain”). She then introduced the planning game (focus on spatial energy planning) and examples that served as the basis and inspiration for the interactive workshop part, in which participants discussed further the presented approaches and technologies including potential for transferring them to their own work contexts.

Current developments of AI approaches in connection with European policies were then interactively discussed in two small groups. The goal was to illuminate opportunities and risks from differing perspectives, particularly regarding requirements for biodiversity data arising from EU policies and regulations such as the RED III Directive, the Nature Restoration Law, and the Taxonomy Regulation. To discuss the opportunities and challenges in a tangible context, participants in the two small groups were provided with maps of landscape sections with differing planning scales (both small and larger scale). Using prepared symbols, participants had the opportunity to mark on the maps to what extent they were already familiar with certain data streams that have already been captured through AI-based approaches. A central focus was on exploring the possibilities of AI-based applications to make the diversity of data in biodiversity research and monitoring manageable, reliable, and accessible. Furthermore, it was discussed how AI-supported automated approaches can be used to supplement existing data collection. Challenges associated with these approaches were also examined.

In the synthesis of the small-group discussions, opportunities and risks associated with the use of AI-based approaches were summarized considering both planning levels. An important insight emerged regarding ways of improving the integration of biodiversity across diverse stages of renewable energy development and even across types of energy production (e.g. solar and wind energy), which could lead to an earlier identification of conflicts of objectives.

Most participants were optimistic about the potential for integrating new AI-supported approaches and discussed several ideas linked to e.g. the monitoring of the condition as well as additional qualitative indicators. Skepticism was based on resources, legal security and responsibilities. A key question was how the generation of baseline data for assessing environmental impacts and planning alternatives, as well as the management and monitoring of measures for biodiversity conservation and promotion, could change using AI. It was discussed what effects this could have on planning quality and early conflict detection. Finally, participants discussed possible further cooperations between science and practitioners regarding quality assurance of AI application as well as the constant technical development.

Workshop Preparation and Conception: Robin Sandfort, Eva Maria Schöll, Jörg Fabian Knufinke, Brady Mattsson, Alexandra Jiricka-Pürner

Moderation: Robin Sandfort, Alexandra Jiricka-Pürner

Presentations: Robin Sandfort, Eva Maria Schöll, Alexandra Jiricka-Pürner

Small Group Moderation: Robin Sandfort, Eva Maria Schöll, Alexandra Jiricka-Pürner

Keywords: AI-based biodiversity monitoring, spatial planning, environmental impact assessment, stakeholder workshop, net-gain conservation strategies.

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Abstract

Wind power installations in Europe: Social acceptance, ecological challenges and innovative solutions

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Ursula Nopp-Mayr¹, Thomas Schauppenlehner³

Although a rapid and comprehensive expansion of renewable energy is necessary to achieve climate goals, the wind energy sector, among others, faces significant challenges. Public acceptance among societal stakeholders is often low, and concerns about the impacts are diverse. As part of the EU Horizon project WIMBY (Wind in my Backyard), various aspects and challenges were addressed, including land use change, potential impacts on wildlife, and the visual impacts of wind turbines on landscapes and their scenic beauty.

More than 15,000 wind turbines across Europe were analyzed using Sentinel-2 satellite imagery to assess land use changes related to wind energy development. The collected data are available for further analysis within the project and is also integrated into a freely accessible interactive online map (<https://map.wimby.eu/>). High-resolution, spatially explicit ecological niche models were developed for 23 wildlife species, including birds, bats, butterflies, and amphibians, revealing that suitable habitats for these species often overlap. Our findings show that wildlife impacts from new wind farms can be substantially reduced by prioritizing the protection of these areas during site selection.

Based on this data analysis, we conducted workshops in a pilot region in the Austrian federal state of Styria to explore local engagement and to gain a better understanding of the trade-offs in the development of wind energy projects. These workshops were designed as interactive planning games, allowing participants to develop various wind energy expansion scenarios and experience an immediate visualization as well as potential impacts on wildlife habitats. These complex spatial relationships were conveyed to non-experts using VR-supported, interactive, and realistic 3D visualizations created from geodata with a game engine. During open discussions in the workshops, the advantages and challenges of wind energy developments were explored, including how such projects could economically and socially benefit the region or potentially affect biodiversity.

Schöll EM, Mikovits C, Bittner K, Baumgartinger-Seiringer M, Diengdoh VL, Kunz F, Nopp-Mayr U, Schauppenlehner T (2026) Windenergie im Spannungsfeld: Gesellschaftliche Akzeptanz, ökologische Herausforderungen und innovative Lösungen

Obwohl ein rascher und umfassender Ausbau erneuerbarer Energie notwendig ist, um die Klimaziele zu erreichen, steht besonders der Windenergie-Sektor vor großen Herausforderungen. Die Akzeptanz unter den gesellschaftlichen Akteuren ist häufig gering und die Bedenken hinsichtlich der Auswirkungen auf das eigene Lebensumfeld sind vielfältig. Im Rahmen des EU-Horizon Projektes WIMBY (Wind in my backyard) wurde neben dem Flächenverbrauch (Landnutzungsänderungen) und den möglichen Auswirkungen auf Wildtiere auch die visuellen Auswirkungen von Windturbinen auf die Landschaft und das Landschaftsbild analysiert.

Mehr als 15.000 Windturbinen in ganz Europa wurden mittels Sentinel-2 Satellitenbildern hinsichtlich der Landnutzungsänderungen untersucht. Die gewonnenen Daten stehen für weiterführende Analysen im Projekt zur Verfügung und werden auch in einer frei zugänglichen, interaktiven Online-Karte des Projektes eingebunden (<https://map.wimby.eu/>). Hochauflösende, räumlich explizite ökologische Lebensraummodelle wurden für 23 Tierarten (u.a. Vögel, Fledermäuse, Schmetterlinge, Amphibien) erstellt. Die Modelle zeigten, dass sich die für die Arten geeigneten Habitate teilweise überschneiden. Die Auswirkungen auf Wildtiere können minimiert werden, wenn der Schutz dieser Gebiete bei der Standortwahl für Windparks beachtet wird.

In einer Pilotregion im Bundesland Steiermark wurden Workshops durchgeführt, um das lokale Engagement und Verständnis für Windenergieprojekte zu untersuchen. Die Workshops wurden als interaktive Planspiele konzipiert, im Rahmen dessen verschiedene Varianten des Windenergieausbaus entwickelt und getestet werden konnten. Um die komplexen räumlichen Zusammenhänge auch Lai*innen vermitteln zu können, wurden aus den verwendeten Geodaten mit einer Game Engine VR-gestützte, interaktive und realitätsnahe 3D-Visualisierungen entwickelt. In einer offenen Diskussion über die Vorteile und Herausforderungen wurde in den Workshops auch erörtert, inwieweit Windenergie-Projekte der Region wirtschaftlich und sozial zugute kommen oder sich auf die biologische Vielfalt auswirken können.

Keywords: habitat suitability, land-use analysis, planning games, stakeholder engagement, wind energy.

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Abstract

Spürhunde – eine traditionelle oder eine moderne Methode im Biodiversitätsmonitoring?

Theresa Walter ¹, Leopold Slotta-Bachmayr ^{1*}, Brigitte Komposch¹

Die klassischen Methoden zum Auffinden und Bestimmen vieler Arten beruhen auf deren optischen Merkmalen, da und dort ergänzt durch akustische Eigenschaften. Gerüche spielen in diesem Zusammenhang eine eher untergeordnete Rolle, obwohl Gerüche aufgrund ihrer Eigenschaften sowohl ein Auffinden von versteckt oder schwer zugänglichen Spezies als auch auf größere Distanz ermöglichen. Zusätzlich können mit Hilfe von Gerüchen auch Arten, ja sogar Individuen, eindeutig identifiziert werden.

Hunde werden seit Jahrtausenden zum Auffinden von Wild im Rahmen der Jagd verwendet. Ihr Einsatz als wissenschaftliche Methode hat aber erst in den letzten 10 Jahren einen immensen Aufschwung genommen. So werden Hunde nicht nur dazu verwendet, den Kot verschiedenster Tierarten zu finden, sie suchen auch nach verborgen lebenden Insekten, unter der Erde ruhenden Amphibien und Reptilien, in geringer Dichte vorkommenden Arten oder werden eingesetzt, um Krankheitserreger zu identifizieren. Durch den Einsatz dieser nicht invasiven Methode vermindert man die Beeinträchtigung von Lebensräumen, wenn man aktiv nach verborgen lebenden Organismen suchen muss. Zudem erhält man bei manchen Arten auch einen weitaus detaillierten Einblick in Populationen, weil Hunde einen Zugang zu manchen Entwicklungsstadien oder zu Individuen in bestimmten Lebensphasen ermöglichen, den man sonst nicht oder nur mit größtem Aufwand erhält. In manchen Bereichen sind Hunde im Vergleich zu Menschen außerdem deutlich effizienter und sparen sowohl Zeit als auch Geld.

Im Rahmen dieses Vortrags bei den Tagen der Biodiversität wurden die Möglichkeiten und Grenzen von Spürhunden im Biodiversitätsmonitorings diskutiert und diese Methode als sinnvolle Ergänzung zu klassischen Erhebungsmethoden dargestellt (vgl. Grimm-Seyfarth et al. 2021).

Walter T, Slotta-Bachmayr L, Komposch B (2026) Detection dogs – a traditional or a modern method in biodiversity monitoring?

The classic methods for collecting and identifying many species are based on their optical characteristics, sometimes supplemented by acoustic properties. Scents play a rather minor role in this context, although their properties enable the detection of hidden or difficult-to-access species, even at greater distances. In addition, species, and even individuals, can be clearly identified using scents.

Dogs have been used for thousands of years to find game during hunting. However, their use as a scientific method has only seen an immense upswing in the last 10 years. Dogs are not only used to find the scats of various animal species, they also search for hidden insects, amphibians and reptiles hibernating underground, species that occur in low density, or are used to identify pathogens. By using this non-invasive method, you can prevent habitats from being affected when you have to actively search for hidden organisms. In addition, you can gain a much more detailed insight into populations for some species because dogs provide access to certain stages of development or to individuals in certain phases of life that would otherwise not be possible or would only be possible with great effort. In some areas, dogs are also significantly more efficient than humans and save both time and money.

As part of this presentation at the Biodiversity Days we discussed the possibilities and limitations of detection dogs in biodiversity monitoring and presented this method as a useful addition to classic survey methods (comp. Grimm-Seyfarth et al. 2021).

Keywords: non-invasive method, scats, mammals, amphibia, reptilia, insects, disease.

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Allgemeine Beiträge | General Submissions

The Northern Birch Mouse (*Sicista betulina*) in Austria: A Review of Occurrence Records and Insights into Its Fragmented Distribution

Christine Resch ^{1*}, Stefan Resch ¹, Jeroen van der Kooij ²

The Northern Birch Mouse (*Sicista betulina*) is among the least studied mammal species in Austria. Despite its wide distribution across Eurasia, populations at the western edge of its range, including Austria, are fragmented and often isolated. This study compiles confirmed records (photo-documented record or voucher) of the species in Austria based on scientific literature, biodiversity databases, museum collections, and field surveys. A total of 78 occurrence record localities (sites) from the period 1964–2025 were identified and georeferenced. The analysis identifies three spatially distinct subareas in Austria: (1) Mühlviertel + = Mühlviertel including a small part of the northwestern Waldviertel (Upper and Lower Austria, north of the Danube), as part of a transboundary occurrence; (2) Styrian Northern Alps–Central Alps = encompassing the Northern Alps of Styria and the adjacent southwestern Central Alpine regions in Salzburg, Styria, and Carinthia; and (3) the Bregenzerwald = a montane region in Vorarlberg in western Austria. The study highlights the need for further targeted surveys to better assess potential genetic isolation among populations within these subareas and to reliably evaluate the actual conservation status of this specialised species.

Resch C, Resch S, van der Kooij J (2026) Die Waldbirkenmaus (*Sicista betulina*) in Österreich: Eine Übersicht der Nachweise und Einblicke in ihre fragmentierte Verbreitung

Die Waldbirkenmaus (*Sicista betulina*) zählt zu den am wenigsten untersuchten Säugetierarten Österreichs. Trotz ihres großen Verbreitungsgebiets in Eurasien sind die Vorkommen am westlichen Rand, worunter in Österreich, fragmentiert und oft isoliert. Diese Studie stellt bestätigte Nachweise der Art (Nachweis durch Fotodokumentation oder Belegexemplar) in Österreich auf Basis wissenschaftlicher Literatur, Biodiversitätsdatenbanken, Museumssammlungen und Feldstudien zusammen. Insgesamt wurden 78 Nachweisstandorte (Fundorte) aus dem Zeitraum 1964–2025 identifiziert und georeferenziert. Die Analyse weist drei räumlich getrennte Teilareale in Österreich aus: (1) Mühlviertel+ = Mühlviertel einschließlich eines kleinen Bereichs im nordwestlichen Waldviertel (Ober- und Niederösterreich, nördlich der Donau) als Teil eines grenzüberschreitenden Vorkommens; (2) Steirische Nordalpen–Zentralalpen = umfassend die nördlichen Kalkalpen der Steiermark sowie die angrenzenden südwestlichen Zentralalpenräume in Salzburg, der Steiermark und Kärnten; und (3) Bregenzerwald = eine montane Region in Vorarlberg in Westösterreich. Die Studie unterstreicht den Bedarf an weiteren gezielten Erhebungen, um eine mögliche genetische Isolation von Populationen innerhalb der Teilareale besser zu beurteilen und die tatsächliche Gefährdungslage dieser spezialisierten Art verlässlich einschätzen zu können.

Keywords: *Sicista betulina*, occurrence record, fragmented populations, small mammals, biogeography, databases, conservation, Austria.

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Introduction

With a body length of 5.8–7.6 cm and a body mass of 5–10 g (up to 13.5 g directly prior to hibernation (Grimmberger 2017)), *Sicista betulina* belongs to the smaller rodent species in Central Europe. A distinctive morphological characteristic is the narrow, dark-pigmented dorsal stripe, approximately 2–3 mm in width, running continuously along the midline from the forehead across the nape and back to the base of the tail. The fur is typically greyish brown to yellowish, and the sparsely haired tail measures approximately 130 % of the body length (Pucek 1982; Grimmberger 2017).

The species' distribution extends from Denmark in the west to Lake Baikal in Russia in the east, and from Romania in the south to Norway, Finland and Russia in the north. At the western end of its range namely in Norway, Sweden, Denmark, Germany, the Czech Republic, and Austria—occurrences are typically small and isolated (Mitchell-Jones 1999; Pilats & Pilats 2009; Meinig et al. 2016). This pattern is also observed in Austria, where traditionally two main occurrence areas were distinguished: a population in the Mühlviertel of Upper Austria, extending across the border into Germany and Czech Republic as part of a transboundary range (Resch et al. 2023a; Poledník et al. 2024), and a second occurrence area in the Austrian Alps, extending from Vorarlberg in the west to the Rax massif in Lower Austria in the east, with most record sites located in the Central Alps (Hable & Spitzenberger 1989; Spitzenberger 2001). Based on the updated dataset compiled in the present study, the Alpine occurrences can be further subdivided into two spatially distinct subareas: (1) the Styrian Northern Alps–Central Alps region and (2) the Bregenzerwald in western Austria.

Sicista betulina inhabits moist, open to semi-open habitats with dense ground vegetation. In the Alps, the species typically occurs in transitional and mosaic habitats such as alpine meadows, open mountain forests, moors, and dwarf-shrub heaths, mostly at higher elevations near the tree line (Hable & Spitzenberger 1989; Spitzenberger 2001). In contrast, in the Mühlviertel, the species also occurs at lower altitudes in extensively managed grasslands, wet meadows, and forest edges (Poledník et al. 2024; Resch et al. 2023a). These specialised habitats are increasingly under anthropogenic pressure. It is assumed that climate change – particularly the loss of wetlands – together with infrastructure development (e.g. ski resorts and renewable-energy facilities) contribute to the ongoing fragmentation of the species' range. In addition, the decline in insect biomass as an important food source represents a further threat. This decline is driven by intensive agriculture, insecticide use, and forestry practices that remove excessive amounts of deadwood (Spitzenberger 2001, 2006; Zulka 2005; Poledník et al. 2024; Resch & Resch 2024). In the Alpine region, both the abandonment of traditional alpine farming and the intensification of land use further reduce habitat availability (Resch & Resch 2021, 2024).

Despite the species' vulnerable status, considerable knowledge gaps remain regarding its current distribution and population structure in Austria. Under the EU Habitats Directive, the conservation status of *S. betulina* was assessed as “unfavourable – inadequate” for the 2013–2018 reporting period (Council Directive 92/43/EEC). The most recent published Red List of endangered animal species in Austria classifies *S. betulina* as “vulnerable (VU)” (Zulka 2005). Regional surveys in Vorarlberg, Salzburg, Upper Austria, Styria, and Carinthia



Fig. 1: Distribution of the Northern Birch Mouse (*Sicista betulina*), with Austria highlighted; Base map: IUCN (2016-vers.3.1). | **Abb. 1:** Verbreitung der Waldbirkenmaus (*Sicista betulina*), Österreich hervorgehoben (Kartengrundlage: IUCN (2016-vers.3.1.)

have yielded valuable data in recent years (Blatt & Resch 2014; Resch & Resch 2019; Resch et al. 2021, 2023b, 2026; van der Kooij et al 2025). Nevertheless, the available information on the species' distribution in Austria remains outdated: the last systematic compilation including years of record and types of evidence was published by Hable & Spitzenberger (1989) and the most recent nationwide distribution map appeared in “*Die Säugetierfauna Österreichs*” in 2001 (Spitzenberger 2001). *Sicista betulina* therefore remains one of the least studied mammal species in Austria. Limited detectability – particularly when using conventional small-mammal survey methods applied in the past – has contributed substantially to this lack of knowledge (Meinig et al. 2015).

Recent technological advances and decreasing costs have enabled the effective use of camera traps even for small mammals, particularly members of Muridae, Arvicolinae, Gliridae, and Soricidae (Di Cerbo & Biancardi 2013; Resch & Blatt 2017b; Mölle et al. 2022; Kleiven et al. 2022; Hopkins et al. 2024; Verhees et al. 2024). As a result, new occurrences of *S. betulina* have been documented through systematic faunistic surveys in recent years (van der Kooij et al. 2016, 2025; Resch & Blatt 2017a; van der Kooij & Möller 2017, 2018; Stille et al. 2018; Schulz & Schulz 2021; Poledník et al. 2024; Resch & Resch 2019, 2024).

The aim of this paper is to compile and present recent occurrence sites of *Sicista betulina* in Austria. This updated dataset is intended to improve understanding of the species' ecological requirements and fragmented distribution and to provide a robust basis for further faunistic surveys.

Material and Methods

Data Compilation on Species Occurrence

To assess the distribution of *S. betulina* in Austria, we conducted a data-driven distributional analysis incorporating confirmed records from the published literature as well as photographic evidence submitted via public reporting platforms. Confirmed records (“C1”)

followed the categorisation used in recent small-mammal syntheses (Kubista et al., 2025; Resch & Resch, 2025; Meinig et al., 2023) and included (i) verified literature records (e.g. photo-documented observations, voucher specimens deposited in collections, or specimens donated, collected, or otherwise secured) and (ii) verifiable photographic submissions from public reporting platforms.

The following data sources were considered:

Scientific publications including record type descriptions: Hable & Spitzenberger (1989), which summarises earlier findings from Gortlieb (1951), Wettstein (1955, 1965a, 1965b), Bauer (1964), Bauer & Wettstein (1965), Hable (1964, 1971a–c, 1976, 1978), Kepka & Mayrhofer (1973), Kepka (1974), Zejda (1970), Petz (1979), Krainer (1986), and Frey & Walter (1986); as well as Spitzenberger (2006), Slotta-Bachmayr & Gressel (1994), Engleder et al. (2005), Engleder & Roth (2006), Sackl et al. (2016), Resch & Resch (2017, 2019, 2020, 2024), Resch et al. (2021, 2023), Poledník et al. (2024) and van der Kooij et al. (2025).

Biodiversity databases: naturbeobachtung.at (Naturschutzbund Österreich 2026), GeoMaus (2026), GBIF.org (2026) including records from iNaturalist (2026) and observation.org (2026), Biodiversity Database Salzburg (Haus der Natur Salzburg 2026), and the Zoological Research Museum Alexander Koenig, Bonn (2026).

Museum collections and specimen records: Landesmuseum Oberösterreich (May 2025), Landessammlungen Niederösterreich (May 2025), Tiroler Landesmuseen (May 2025), inatura – Erlebnis Naturschau Dornbirn (May 2025), Universalmuseum Joanneum (May 2025), Landesmuseum Kärnten (May 2025), and Naturhistorisches Museum Wien (May 2025).

Duplicate records were removed, giving preference to published sources as these are publicly accessible and often provide more detailed information on individual records (e.g. habitat data or the type of voucher). To avoid overrepresentation of intensively surveyed localities – particularly in subsequent assignments to ecoregions – only the most recent record date was retained where multiple records referred to the same site, as the objective of this study was to compile occurrence sites rather than to analyse temporal reporting intensity at individual localities. For the purpose of this study, an occurrence site was defined as being separated from any other site by at least 500 m; records falling within this distance were treated as referring to the same site. This 500 m threshold was chosen as a conservative operational rule to reduce pseudo-replication by consolidating nearby records that likely refer to the same locality into a single occurrence site. For systematic camera-trap studies (Resch & Blatt 2017a, 2017b; Resch & Resch 2019, 2020, 2024; Resch et al. 2021, 2023b; van der Kooij et al. 2025), a representative point of the study area was used instead of individual detection locations. The resulting dataset therefore represents occurrence sites and is not intended to provide a complete list of all individual reports per site.

The resulting records, spanning the period from 1964 (the first confirmed occurrence of *Sicista betulina* in Austria; Hable 1964) to 2025, were georeferenced in the WGS 84 coordinate system with a precision of at least two decimal degrees, corresponding to a positional uncertainty of approximately 1 km.

Visualisation and Spatial Analysis

The dataset was mapped in two formats: (1) as exact occurrence points grouped into four time intervals (1964–1990, 1990–2009, 2010–2019, and 2020–2025), and (2) as spatially aggregated records within a 10 km × 10 km ETRS89-LAEA grid. This grid corresponds to the standard used for distribution mapping in Article 17 reporting under the Habitats Directive (European Environment Agency 2020) and thus ensures national and international comparability. Moreover, this grid resolution provides a robust overview of broad-scale patterns and reduces artefacts caused by uneven sampling effort, which can influence finer grids. Within each grid cell, only the most recent record was retained and assigned to the same four time intervals to ensure comparability between point-based and grid-based visualizations. The time intervals were defined based on the temporal distribution of the available data: they begin with the first confirmed record in Austria (1964) and represent a stepped temporal resolution, with older periods aggregated more broadly, while recent records (2020–2025) were shown as a separate class to highlight their recency.

Subsequently, all occurrence points were spatially assigned to five out of ten Austrian ecoregions according to Umweltbundesamt GmbH (2024): Central Alps – Central part; Central Alps – Southeastern part; Granite and Gneiss Highlands; Eastern Northern Alps, Western and Central Northern Alps,

Results

A total of 80 verified occurrence sites of *Sicista betulina* in Austria were compiled. These sites originate from the following sources:

- **Scientific publications (n = 58):** Hable & Spitzenberger (1989) (32), Spitzenberger (2006) (3), Slotta-Bachmayr & Gressel (1994) (1), Engleder et al. (2005) (2), Petz (1979) (1), Engleder & Roth (2006) (1), Sackl et al. (2016) (1), Resch & Blatt (2017a) (1), Resch & Resch (2019) (2), Resch & Resch (2020) (1), Resch et al. (2021) (3), Resch et al. (2023) (3), Poledník et al. (2024) (1), Resch & Resch (2024) (2), van der Kooij et al. (2025) (5) and Resch & Resch (2026) (1)
- **Biodiversity databases (n = 10):** naturbeobachtung.at (2), GeoMaus (1), GBIF.org (7; including iNaturalist [1], observation.org [2], Biodiversity Database Salzburg [3], Zoological Research Museum Alexander Koenig, Bonn [1])
- **Museum collections (n = 8, unpublished records not included in the other data sources):** Naturhistorisches Museum Wien (6), inatura – Erlebnis Naturschau Dornbirn (2)

The records are distributed across the following Austrian ecoregions (Fig. 1):

- **Granite and Gneiss Highlands:** Eleven records originate from the Mühlviertel in Upper Austria (10) and the Waldviertel in Lower Austria (1). This region is situated in northern Austria and forms part of the ecoregion Granite and Gneiss Highlands, a geologically distinct unit within the southern margin of the Bohemian Massif.

- Eastern Northern Alps: nine records originate from the eastern part of the Northern Alps within the Styrian Northern Alps.
- Central Alps (Central and Southeastern part): The majority originate from this ecoregion ($n = 50$), with 37 records located in the central part and 13 in the south-eastern part.
- Western and Central Northern Alps: eight records originate from the western part of the Northern Alps, specifically the Bregenzerwald region in Vorarlberg.

Based on the spatial clustering of records, three distinct distributional subareas were delineated (Fig. 2):

1. Mühlviertel+ (Subarea 1): Includes parts of the Bohemian Forest, the *Leonfelder Hochland and the Freiwald* region (Upper Austria), with “+” indicating a small adjacent area in the north-western Waldviertel (Lower Austria). The occurrence of *Sicista betulina* in the northern Mühlviertel forms part of a transboundary population range extending along the Austrian–Czech–German border (Poledník et al. 2024). Within the Austrian range considered here, occurrence sites have been documented in the Bohemian Forest between 1968 and 2024: Plöckenstein, Schwarzenberg am Böhmerwald municipality (most recently in 2019; Resch et al. 2023b), Klaffer am Hochficht municipality (last recorded in 1968; Petz 1979), and Aigen-Schlägl municipality (most recently in 2024; Resch & Resch 2026). Further east, confirmed occurrence sites are known from the eastern Mühlviertel – Sandl municipality (most recently in 2005; Engleder et al. 2005), Leopoldschlag municipality (2016; Resch & Blatt 2017a), and Liebenau municipality (2025; GeoMaus 2025). In addition to the Mühlviertel, a small adjacent area in the Waldviertel of Lower Austria has been documented (Poledník et al. 2024), with the most recent record from 2017 in Stadlberg, municipality of Bad Großpertholz.

2a. Styrian Northern Alps (Subarea 2a): Covers the Ennstal Alps, the Hochschwab Group, and the *Mürzsteiger Alps* in the federal state *Styria*. The known distribution area comprises three mountain ranges: the Ennstal Alps, the Hochschwab Group, and the Mürzsteg Alps. In the Ennstal Alps, the most recent record was obtained during a mapping survey in Gesäuse National Park in 2019, specifically at the Scheucheggalm and Sulzkaralm (Resch & Resch 2019). In the Hochschwab Group, an incidental observation was documented near the Fölzsattel in 2015 (iNaturalist). In the Mürzsteg Alps, the most recent confirmed record dates to 2021 (naturbeobachtung.at). As outlined by Resch & Resch (2024), populations in the Styrian Northern Alps are assumed to be isolated due to the region’s pronounced topographic structure. The Paltental Valley, a prominent longitudinal valley oriented from south-east to north-west, constitutes a natural boundary between the Northern and Central Alps and likely acts as a present-day barrier to dispersal into subarea 2b.

2b. Central Alps (Subarea 2b): Including the High and Low Tauern, as well as the Nockberge; covering the federal states of Salzburg, Styria, and Carinthia. The distribution range includes High and Low Tauern as well as the Nockberge. Within this range, occurrences seemingly are highly fragmented, and transverse alpine valleys may represent important topographic barriers to dispersal. Due to the absence of systematic survey efforts, the

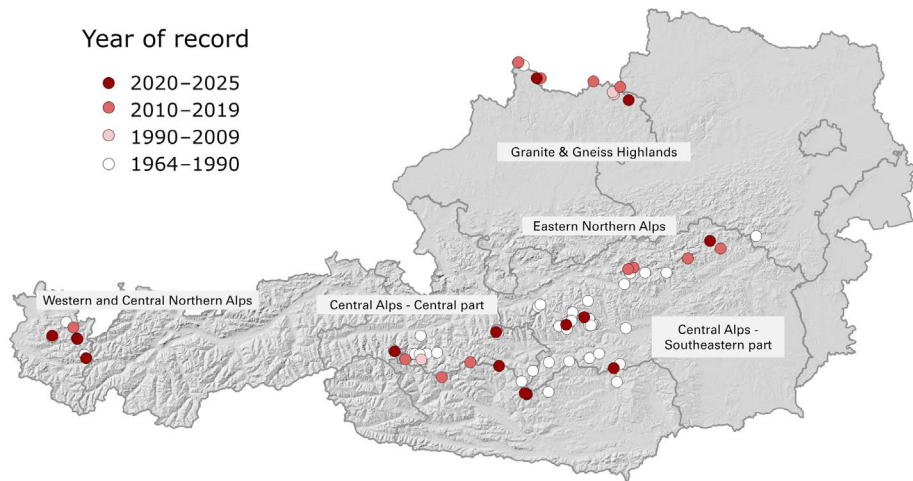


Fig. 2: Record localities of the Northern Birch Mouse (*Sicista betulina*) in Austria (compiled as occurrence sites documented by photo records or voucher specimens), shown within major ecoregions (grey line). Base map: DEM – Digital Elevation Model Land Kärnten (2015), Ecoregions: Umweltbundesamt GmbH (2024). | **Abb. 2:** Nachweise der Birkenmaus (*Sicista betulina*) in Österreich (zusammengestellt als Vorkommen, die durch Fotoaufnahmen oder Belegexemplare dokumentiert sind), dargestellt innerhalb der wichtigsten Ökoregionen (graue Linie). Basiskarte: DGM – Digitales Geländemodell des Landes Kärnten (2015); Ökoregionen: Umweltbundesamt GmbH (2024).

degree of isolation among subpopulations cannot yet be reliably assessed. The species' presence in the High Tauern (Glocknergruppe, Goidberggruppe and Ankoglergruppe) is supported by recent records from the municipalities Fusch an der Großglocknerstraße (2019; Resch & Resch 2020) and Kaprun (2020; naturbeobachtung.at). In the Low Tauern, records originate from the Radstädter, Schladminger, and Wölzer Tauern, with recent records from 2021–2025 in the municipalities St. Peter am Kammerberg and Pusterwald (Resch & Resch 2024), as well as Muhr and Untertauern (observation.org). The distribution further extends into the Nock Mountains of Carinthia, as confirmed by recent records from 2024 in the municipalities of Bad Kleinkirchheim and Hüttenberg (van der Kooij et al. 2025).

3. Bregenzerwald (Subarea 3): Most record localities are situated within the Bregenzerwald region in Vorarlberg (Spitzenberger 2006; Resch et al. 2021). This area represents the westernmost known occurrence of the species in Austria and, together with Denmark and Norway, marks the known western limit of its distribution in Europe. Recent records from 2019–2025 originate from the sites Krüz, Bellischegg Alpe, and Sulzried Alpe (Resch & Resch 2021), as well as Damüls (inatura Erlebnis – Naturschau Dornbirn 2025). The populations in this subarea are likely connected to those in the adjacent Allgäu region in Bavaria, Germany (Stille et al. 2018; Meinig et al. 2015), but are otherwise likely isolated from other occurrences in Europe. Targeted surveys may reveal additional occurrences in adjacent Tyrol (Resch et al. 2021).

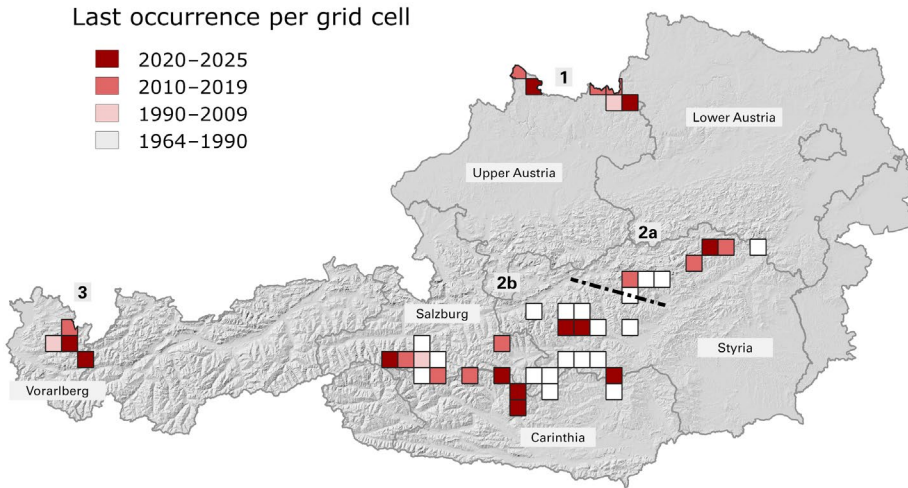


Fig. 3: Occurrence of *Sicista betulina* in Austria (compiled as occurrence sites documented by photo records or voucher specimens) displayed within a 10km grid. Subareas are delineated as follows: 1 – Mühlviertel+; 2a – Styrian Northern Alps; 2b – Central Alps; 3 – Bregenzerwald and Lechtal Alps. Federal state boundaries are shown as grey lines. (Base map: DEM – Digital Elevation Model (Land Kärnten 2015), Grid: ETRS89-LAEA 10km; Federal state boundaries: BEV 2025). | **Abb 3:** Vorkommen von *Sicista betulina* in Österreich (dargestellt als durch Fotobelege oder Belegexemplare dokumentierte Fundorte) auf Basis eines 10-km-Rasters. Die Teilgebiete sind wie folgt abgegrenzt: 1 – Mühlviertel+; 2a – Steirische Nordalpen; 2b – Zentralalpen; 3 – Bregenzerwald und Lechtaler Alpen. Die Bundesländergrenzen sind als graue Linien dargestellt. (Basiskarte: DGM – Digitales Geländemodell (Land Kärnten 2015), Raster: ETRS89-LAEA 10km; Bundesländergrenzen: BEV 2025).

A complete list of all occurrence sites is provided as a table in the Supplementary Material. The table includes (1) a continuous unique ID (1–78), (2) year, (3) type of evidence, (4) locality (assigned to the nearest locality according to Statistik Austria – data. statistik.gv.at (2025) (5) municipality, (6) district and (7) federal state (5–7: based on administrative boundaries (BEV 2025) (8) data source with a link for further information (9) ecoregion based on Umweltbundesamt GmbH (2025); and (10) Cell-Code, (11) EofOrigin (12) NofOrigin (10–12: ETRS-LAEA 10km Austria grid; Pfeifer 2011).

Discussion

The results show that *Sicista betulina*, although rare, is still present in suitable habitats in Austria. Its main distribution area remains the Alps, including the Bregenzerwald, the Central Alps in Salzburg, Carinthia, and Styria, as well as the Styrian Northern Alps. A further occurrence is located in the Mühlviertel region within the Bohemian Massif (Fig. 1 and 2).

The results of this study indicate an apparently fragmented distribution of *Sicista betulina* in Austria. The pronounced spatial separation of populations – particularly between the subareas 1 Mühlviertel+, 2 Styrian Northern Alps and Central Alps and 3 Bregenzerwald – strongly suggests population isolation. All three occurrence areas are relatively small, and even within these otherwise contiguous ranges, ongoing habitat loss may lead to further fragmentation and isolation of subpopulations. Such isolation may impede gene flow, potentially resulting in reduced genetic diversity and increased susceptibility to environmental change. Anthropogenic pressures, including wetland drainage, infrastructure development, and the intensification of land use in both agriculture and forestry (Spitzenberger 2001, 2006; Resch & Resch 2021, 2024) have likely exerted severe pressure on local populations. Climate-change-related effects such as altered precipitation regimes and increased temperature variability have probably resulted in less stable snow cover. This instability may have compromised the species' ability to endure prolonged and harsh winter conditions during torpor, potentially leading to the extirpation of local populations (van der Kooij et al. 2025). Consequently, genetic isolation among subpopulations is likely to have increased over the past 50 years.

However, due to species' historically poor detectability, additional occurrences may still remain undetected. Some populations that currently appear isolated may therefore still be functionally connected. Undiscovered populations are of particular importance for conservation planning. Because species occurrences are typically considered in planning and permitting procedures only when they are known; likewise, the implementation of targeted habitat improvement measures depends on reliable information on current presence. Targeted surveys employing specialised camera traps should therefore be conducted, especially in apparent distribution gaps and in areas lacking recent records. Continued use of citizen-science platforms may further contribute valuable occurrence data.

Finally, a comprehensive genetic analysis encompassing samples from the entire Austrian distribution range is recommended to assess genetic diversity and levels of isolation among populations. If preserved museum specimens allow for reliable DNA extraction, comparisons between historical and contemporary genetic variation should be undertaken to evaluate temporal changes in genetic structure.

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Electronic Supplement

S1: List of all occurrence sites | **S1:** Liste aller Fundorte

https://www.zobodat.at/pdf/supp/Resch_et_al_Supplement.xlsx

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Fish ecology and diversity in the lower Vjosa river and its delta

Spase Shumka ^{1*}, Nertila Muçollari ¹, Paul Meulenbroek ²

The lower Vjosa river and its delta support a diverse ichthyofauna comprising at least 34 fish species, of which 30 are native. Among these, eight species are endemic to the Balkan Peninsula. The family Cyprinidae is the most species-rich, represented by 12 species, followed by Mugilidae with five species. Both Salmonidae and Acipenseridae are represented by two species each, while ten other families are each represented by a single species. Four non-native species – *Pseudorasbora parva*, *Oncorhynchus mykiss*, *Carassius gibelio*, and *Gambusia holbrooki* – have been introduced into the Vjosa basin.

The lower river also supports several estuarine and marine-associated species, including the European eel (*Anguilla anguilla*), mullets, gilthead seabream (*Sparus aurata*), European seabass (*Dicentrarchus labrax*), flounder (*Platichthys flesus*), and soles (*Solea spp.*). Notably, *Atherina boyeri* and *Aphanius fasciatus* are numerically dominant, underscoring their ecological relevance in this transitional habitat.

Fish assemblages in the lower Vjosa and its delta are affected by multiple interacting stressors, including upstream damming, in-stream gravel extraction, pollution, land-use change, urban development, non-native species, and climate change. Understanding the cumulative and interactive effects of these pressures is essential for the development of effective conservation and river management strategies.

Shumka S, Muçollari N, Meulenbroek P (2026) Ökologie und Artenvielfalt der Fische des Unterlaufs der Vjosa und ihres Deltas

Der Unterlauf der Vjosa und ihr Delta bieten Lebensraum für eine vielfältige Fischfauna von mindestens 34 Arten, wovon 29 heimisch sind und acht davon endemisch für die Balkanhalbinsel. Die artenreichste Familie sind die Karpfenfische (Cyprinidae) mit 12 Arten, gefolgt von den Meeräschen (Mugilidae) mit fünf Arten. Lachsfische (Salmonidae) und Acipenseridae sind jeweils mit zwei Arten vertreten, während zehn weitere Familien jeweils eine einzige Art aufweisen. Daneben wurden vier nicht heimische Arten ins Vjosa-Becken eingeführt: *Pseudorasbora parva*, *Oncorhynchus mykiss*, *Carassius gibelio* und *Gambusia holbrooki*.

Die Fischfauna des Unterlaufs umfasst mehrere Arten, die an Ästuar und das Meer gebunden sind, wie den Europäischen Aal (*Anguilla anguilla*), verschiedene Meeräschenarten (*Mugil cephalus*, *Liza ramada*, *Liza saliens* und *Chelon labrosus*), die Goldbrasse (*Sparus aurata*), den Wolfsbarsch (*Dicentrarchus labrax*), Plattfische (*Platichthys flesus*) und Seezungen (*Solea spp.*). Bemerkenswert ist die zahlenmäßige Dominanz von *Atherina boyeri* und *Aphanius fasciatus*, die auf ihre zentrale ökologische Rolle in diesem Übergangshabitat hinweist.

Die Fischgemeinschaften im unteren Vjosa-Fluss und seinem Delta sind komplexen und vielschichtigen Umweltbelastungen ausgesetzt. Dazu gehören anthropogene Eingriffe wie Staudämme flussaufwärts, Kiesabbau im Fluss und verschiedene Formen der Verschmutzung. Hinzu kommen Landnutzungsänderungen, städtische Entwicklung, die Einschleppung gebietsfremder Arten sowie der Klimawandel. Das Verständnis der kumulativen und synergistischen Auswirkungen dieser Stressoren ist entscheidend, um wirksame Strategien für den Schutz der Biodiversität und ein nachhaltiges Flussmanagement zu entwickeln.

Keywords: ichthyofauna, conservation, protected area, Balkan rivers, endemic species, delta ecosystem, habitat heterogeneity.

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Introduction

According to the Palearctic Habitat Classification (Devillers & Devillers-Terschuren, 1996), Albania encompasses two biogeographical regions: the Mediterranean and the Alpine. The majority of the country falls within the Mediterranean region, including the entire southern and northwestern areas. As a result of its geographic and ecological complexity, Albania is recognized as one of the countries with the highest freshwater fish diversity in Europe, hosting over 101 species, including marine euryhaline forms (Shumka et al. 2023). Furthermore, the ichthyofauna is distinguished by a large number of endemics, including 10 Balkan endemic species that only exist in the waters of Albania and one of the neighboring countries (Tab. 1).

Vjosa basin (Fig. 1) provides a unique opportunity to test biogeographical theories, as it is characterized by a young geology with distinctive geographical barriers and highly connected hydrographic networks (Bănărescu 2004; Oikonomou et al. 2014). The comparatively high fish diversity of the Vjosa river and the correspondingly particular conservation needs are confirmed by recent publications (Shumka et al. 2018a, 2023b; Meulenbroek et al. 2018, 2020; Hammerschmied 2019).

The fundamental goal of the Water Framework Directive (WFD 2000/60/EC) is to achieve good ecological status, which is assessed using biological quality elements (BQEs) that are sensitive to nutrient enrichment and hydromorphological pressures. (Lyche-Solheim et al. 2013; Dudley et al. 2013). As a sensitive component to changes in water condition and nutrient concentrations, fish are classified among the BQEs. As a result, countries undergoing European integration must incorporate fish into monitoring methods as a useful indication for evaluating the trophic status of aquatic ecosystems. Due to various human activities, freshwater environments and river systems in particular are among the most endangered ecosystems in the Mediterranean region (Weiss et al. 2018). The introduction and proliferation of alien species have one of the most detrimental effects on these ecosystems. However, overfishing, habitat destruction, pollution, hydrological and climate change frequently have a combined, synergistic effect on the impacts of alien and invasive fish species on the native fauna (Dudgeon et al. 2006; Buj et al. 2023). Alien species are recognized as a serious threat to the local ichthyofauna and are identified as such in Albania's Biodiversity Strategy and Action Plan (MoE 2015).

The native ichthyofauna of the Vjosa reflects the rich geological past and geographic position of the basin, given the large number of near-endemic species (species almost entirely found within Vjosa territory and most of them are found in two lake systems shared with neighboring countries i.e., Albania and Greece) and Balkan endemics (species restricted to the southern Balkans, specifically, to the Southeast Adriatic). The genera *Oxynoemacheilus*, *Cobitis* and *Pelagus* include near endemic and endemic Balkan species. The alien fish that have been introduced within Albanian river basins from a number of continents, originating

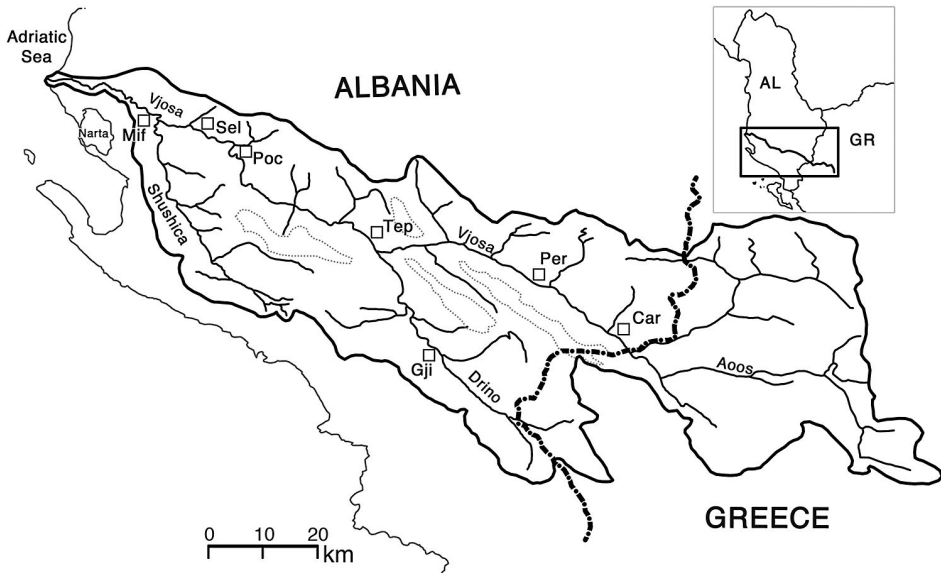


Fig. 1: Map of the study area showing the location of the Vjosa river (Source: VjoSusDev-APPEAR Project No. 251). | **Abb. 1:** Karte des Untersuchungsgebiets mit der Lage des Flusses Vjosa. (Quelle: VjoSusDev-APPEAR, Projektnummer 251)

from various biogeographic areas has also reached the Vjosa basin. These species have a broader range of ecological tolerances and occupy a spectrum of ecological niches (*Pseudorasbora parva*, *Gambusia holbrooki*, *Carassius gibelio*, etc.).

Because alien species differ in both establishment success and ecological impact, this study pays particular attention to interactions between the native Mediterranean killifish (*Aphanius fasciatus*) and the introduced mosquitofish (*Gambusia holbrooki*). Some introduced species may establish only small populations and exert minimal or no measurable impact on native communities (Buj et al. 2023). In contrast, other species can rapidly expand in abundance and distribution, exerting profound ecological pressures. These species, due to their high adaptability and dispersal capacity, often become invasive, significantly disrupting local ecosystems and threatening native biodiversity.

Introduced fish species can have both direct impacts on native fauna and indirect effects on ecosystem structure and function, often through resource competition or trophic interactions. Their successful establishment and spread are frequently facilitated by anthropogenic stressors such as water pollution, habitat degradation, and shifts in the composition of native fish communities. These changes can have significant ecological consequences, including alterations in community structure, declines in the abundance of native species – particularly those that are rare, endemic, or threatened – and, in extreme cases, local extinctions.

After Sovinc (2021) the Vjosa ecosystem offers numerous services to people, including biodiversity conservation, water purification, flood prevention, healthy fisheries, landscape, and culture. Increased fishing pressure and the use of non-friendly gears (which increases fishing pressure but also has destructive impacts) were among concerns for the fishers. A common local fishing technique known as “Bilançiera” is non-selective, and their very large quantity directly affects both the migration density and the rate of recruitment. It is a lift net fishing that consists in obliquely immersing a large circular sieve with loose mesh and rattan frame, which the fisherman maneuvers like a harrow. It is reserved to well-trained adult fishermen and are solely set up in a moderate water flow. Lift net fishing takes place preferably during moonless nights, but also during daylight right after heavy rain that has increased the turbidity of the water. Further to that the land-use changes, lack of wastewater treatment facilities along the Vjosa stretch, solid waste pollution, increased sedimentation rates and turbidity, intensive fishing within Adriatic coast and Mediterranean, etc., are likely to be the main factors impacting aquatic ecosystems and ultimately causing the apparent reductions in fish yields (Shumka et al. 2023b).

Changes in land-use and hydrological variation affect large areas over lengthy periods, so they are not amenable to accurate observation or recall by casual observers who work in restricted locales. The discrepancies between fishermen’s perceptions and, in some cases, their own actual data and the true underlying environmental causes of changes highlight the need for more representative long-term monitoring data on key ecosystem attributes and the calibration of any interviews against actual monitoring data.

This study assesses the ecological characteristics and ichthyofaunal diversity of the lower Vjosa river and its delta, with particular emphasis on the distribution of native, endemic, and non-native fish species. It also evaluates major environmental pressures and outlines key conservation challenges and opportunities.

Materials and Methods

We used a fish database generated from the Vjosa sampled during the period of 2013–2024. The fish data was created as part of a newly established Vjosa Wild River National Park approach, supplemented by additional data from the authors. Further on a systematic review of the literature was conducted, following the guidelines of Haddaway et al. (2015). The work was focused on peer-reviewed studies, PhD and Master’s theses, and scientific reports regarding Vjosa basin that were written in English and published online (Fig. 2). The data search was conducted in three comprehensive databases of scholarly publications – Web of Science, Google Scholar, and Scopus – between January 2000 and December 2024. A preliminary assessment was conducted of a subset of articles prior to the main search, to determine the search-string combination to utilize. All results were evaluated for relevancy and to avoid papers that were not related to our focus for each search-string. The comparative analyses and relative placement of 11 Albanian basins according to their fish population using Multi-Dimensional Scaling was based on Shumka et al. 2023a. The discussions with regard to interrelationship and competition among native Mediterranean killifish (*Aphanius fasciatus*) and introduced mosquito fish (*Gambusia holbrooki*) are based on recent data collected during the years 2023–2024.

Results and Discussions

33 fish species have been reported for the Vjosa as of 2018 (see Tab. 1), with 17 of them being freshwater species, 10 being saltwater species, four exhibiting anadromous activity, one species (*Anguilla anguilla*) being catadromous, and one species (*Atherina boyeri*) exhibiting amphidromous behavior. With nine out of 26 native species (27 percent) being endemic to the Balkans, the Vjosa exhibits a high degree of endemism aside from records of four alien species. The majority of fish species in the Vjosa belong to the lithophilic spawning guild (15 species, 45 percent) followed by pelagophilic (nine species, 27 percent) and phytophilic (five species, 15 percent). Two species are categorized as being both lithophilic and phytophilic.

Tab. 1: Fish species recorded in the Vjosa river. Abbreviations: RL, Red List; N, native; A, alien; VU, Vulnerable; EN, Endangered; LR, Lower Risk; LC, Least Concern; CR, Critically Endangered; NT, Near Threatened; E, endemic; NE, near-endemic; EB, Balkan endemic; II, listed in Annex II (strictly protected fauna species); III, listed in Annex III (protected fauna species); rh, rheophilic; ind, indifferent; lim, limnophilic; pel, pelagophilic; lith, lithophilic; phy, phytophilic; ovo, ovoviviparous; omn, omnivorous; ins, insectivorous; herb, herbivorous; pisc, piscivorous; eur, euryhaline | **Tab. 1:** Im Fluss Vjosa nachgewiesene Fischarten. Abkürzungen: RL, Rote Liste; N, heimisch; A, gebietsfremd; VU, gefährdet (Vulnerable); EN, stark gefährdet (Endangered); LR, geringes Risiko (Lower Risk); LC, nicht gefährdet (Least Concern); CR, vom Aussterben bedroht (Critically Endangered); NT, potenziell gefährdet (Near Threatened); E, endemisch; NE, nahezu endemisch; EB, Balkan-Endemit; II, in Anhang II gelistet (streng geschützte Tierarten); III, in Anhang III gelistet (geschützte Tierarten); rh, rheophil; ind, indifferent; lim, limnophil; pel, pelagophil; lith, lithophil; phy, phytophil; ovo, ovovivipar; omn, omnivor; ins, insektivor; herb, herbivor; pisc, piscivor; eur, euryhalin

Species	Categories		Albanian RL	IUCN	Bern Convention	Categories	Species notations	Rheophilic guild	Spawning guild	Feeding guild	References
<i>Acipenser naccarii</i>	N	EN	CR	II	N		rh	lith	om		Poljakov et al. 1958; Rakaj 1995
<i>Acipenser sturio</i>	N	EN	CR	II	N		rh	lith	om		Poljakov et al. 1958; Rakaj 1995
<i>Alburnoides aff. prespensis</i>	N		EN		N	EB	rh	lith	om		Poljakov et al. 1958; Rakaj 1995; Stlerandova et al. 2016; Shumka et al. 2023
<i>Alburnus scoranza</i>	N		NT		N	EB	ind	lith-phy	ins		Rakaj 1995; Kottelat & Freyhoff 2007; Shumka et al. 2010; Barbieri et al. 2015
<i>Alosa fallax</i>	N		NT		N		rh	lith	pis		Poljakov et al. 1958; Rakaj 1995; Kottelat & Freyhoff 2007; Shumka et al. 2023
<i>Anguilla anguilla</i>	N		CR		N		ind	pel	om		Shumka et al. 2010; Moulenbroeck et al. 2020
<i>Atherina boyeri</i>	N		LC		N		lim	phyt	ins-her		Poljakov et al. 1958; Rakaj 1995; Kottelat & Freyhoff 2007; Shumka et al. 2023

Species	Categories		Albanian RL	IUCN	Bern Convention	Categories	Species notations	Reophilic guild	Spawning guild	Feeding guild	References
<i>Aphanius fasciatus</i>	N	EN	LC	II	N		lim	phyt	pis		Poljakov et al. 1958; Rakaj 1995; Kottelat & Freyhoff 2007; Shumka et al. 2010
<i>Barbus prespensis</i>	N	LR	NT		N	EB	lim	phyt	ins-her		Crivelli 1996; Markova et al. 2010; Shumka et al. 2010; Kottelat & Freyhoff 2007
<i>Carassius gibelio</i>	A				A		ind	phyt	ins-her		Poljakov et al. 1958; Rakaj 1995
<i>Chelon aurata</i>	N				N		pel	pel	ins-her		Poljakov et al. 1958; Rakaj 1995; Kottelat & Freyhoff 2007; Shumka et al. 2010
<i>Chelon labrosus</i>			LC		N		pel	pel	ins-her		Poljakov et al. 1958; Rakaj 1995; Kottelat & Freyhoff 2007; Shumka et al. 2023
<i>Chelon ramada</i>	N				N		pel	pel	ins-her		Poljakov et al. 1958; Rakaj 1995; Kottelat & Freyhoff 2007; Shumka et al. 2023
<i>Chelon saliens</i>	N				N		pel	pel	ins-her		Rakaj 1995; Kottelat & Freyhoff 2007
<i>Chondrostoma vardarensis</i>	N	LR	NT	III	N	EB	rh	lith	herb		Crivelli 1996; Shumka et al. 2010; Kottelat & Freyhoff 2007; Gieger et al. 2014
<i>Cobitis ohridana</i>	N	LR	NT		N	EB	lim	phyt	ins		Crivelli 1996; Shumka et al. 2010; Kottelat & Freyhoff 2007; Sanda et al. 2010
<i>Ctenopharyngodon idella</i>	A		LC		A		lim	phyt	herb		Shumka et al. 2023
<i>Dicentrarchus labrax</i>	N		NT		N		pel	pel	pisc		Rakaj 1995; Shumka et al. 2010
<i>Gambusia holbrooki</i>	A		LC		A		lim	ovo	ins		Rakaj 1995; Kottelat & Freyhoff 2007; Shumka et al. 2008; Shumka et al. 2010
<i>Gobio skadarensis</i>	N	LR	NT		N	EB	ind	lith-phy	ins		Crivelli 1996; Shumka et al. 2010; Kottelat & Freyhoff 2007; Sanda et al. 2010
<i>Gobius sp.</i>	N				N		ind	lith-phy	ins		Shumka (non-published data)
<i>Luciobarbus albanicus</i>	N		LC		N	EB	lim	phyt	ins-her		Poljakov et al. 1958; Rakaj 1995; Crivelli 1996
<i>Mugil cephalus</i>	N		LC		N		pel	pel	ins-her		Poljakov et al. 1958; Rakaj 1995; Kottelat & Freyhoff 2007
<i>Oncorhynchus mykiss</i>	A				A		rh	lith	ins-pisc		Poljakov et al. 1958; Rakaj 1995; Kottelat & Freyhoff 2007; Shumka et al. 2010

Species	Categories Albanian RL	IUCN	Bern Convention	Categories	Species notations	Reophilic guild	Spawning guild	Feeding guild	References
<i>Oxynoemacheilus pindus</i>	N	NT		N	NE	rh	lith	ins	Kottelat & Freyhoff 2007; Shumka et al. 2010
<i>Pachychilon pictum</i>	N	NT	III	N	EB	lim	lith- phyto	omn	Poljakov et al. 1958; Rakaj 1995; Kottelat & Freyhoff 2007; Shumka et al. 2010
<i>Pelagus thesproticus</i>	N	NT		N	NE	lim	phyt	ins- herb	Poljakov et al. 1958; Rakaj 1995; Kottelat & Freyhoff 2007
<i>Petromyzon marinus</i>	N	VU	LC	III	N	pel	lith	pisc	Poljakov et al. 1958; Rakaj 1995
<i>Platichthys flossus</i>	N	VU	LC		N	pel	pel	ins- herb	Rakaj 1995; Shumka et al. 2010
<i>Pseudonasa bora parva</i>	A				A	ind	lith	omn	Rakaj 1995; Kottelat & Freyhoff 2007; Shumka et al. 2008; Shumka et al. 2010
<i>Sparus aurata</i>	N	LC		N		pel	pel	pisc	Rakaj 1995; Kottelat & Freyhoff 2007; Shumka et al. 2008
<i>Squalius platyceps</i>	N	LC		N	EB	ind	lith	omn	Kottelat & Freyhoff 2007; Shumka et al. 2023
<i>Solea sp.</i>	N			N		pel	lith	omn	Shumka unpublished data
<i>Syngnathus abaster</i>	N	LC		N		eur	ovo	omn	Shumka et al. 2023

The transitional habitats and fish of the lower river and delta of the Vjosa – a contrast between rare/endemic and introduced fish species

Aphanius fasciatus vs. *Gambusia holbrooki* – local records of potential alien invasive pressures on Mediterranean killifish. Aside from the fact that the relationship between these two species is not well studied, there is little literature data confirming the aggressive impacts of *Gambusia holbrooki* on the genus *Aphanius* and other related small-sized native fishes in other regions of Mediterranean (Pyke 2005; Kalogianni et al. 2014; Valdesalici et al. 2015). *A. fasciatus* spawns in the benthic submerged vegetation, with a spawning period from March to September, depending on the geographic position of the given population (Kottelat & Freyhof 2007). Populations in Italy spawn from March to June, in Greece from April to July and in Corsica from April to September (Leonardos & Sinis 1998; Marčić et al. 2015; Shumka et al. 2023b). Spawning takes place on the bottom and in submerged vegetation. The species is short-lived and maturity is reached within less than a year. Reproductive strategies of *Aphanius fasciatus* show the typical adaptations to the unstable and unpredictable environment of transitional waters, such as batch spawning and early sexual maturation (Leonardos & Sinis 1998). Our observational evidence shows that they reproduce in spring and/or early summer in the Vjosa delta complex (Shumka et al. 2023b).

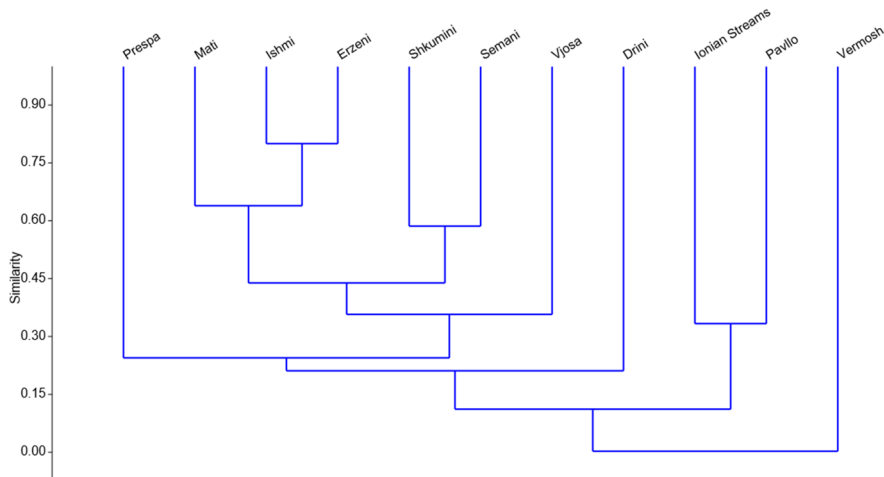


Fig. 2: Relative positioning of 11 Albanian river basins based on their fish assemblages using multidimensional scaling (MDS). (Source: Shumka et al. 2023a) | **Abb. 2:** Relative Anordnung von elf albanischen Einzugsgebieten anhand ihrer Fischgemeinschaften mittels multidimensionaler Skalierung (MDS). (Quelle: Shumka et al. 2023a)

The Mediterranean killifish (*Aphanius fasciatus*) is native to Albanian inland and coastal transitional waters. This small species (typically 4–6 cm total length) feeds mainly on zooplankton and may also consume eggs, larvae, and aquatic stages of mosquitoes and midges (Zogaris 2017; Shumka et al. 2023a). *A. fasciatus* is not a migratory fish, but in normal conditions it spreads beyond its resident areas. Our survey on the lower flow of the Vjosa, the Narta lagoon, and lowland drainage channels has shown that, at the wetlands complex, *Aphanius*' distributional pattern expands and contracts depending on meteorological conditions and seasonal drought effects on the local populations. According to Zogaris (2017), by late spring they are breeding and locally abundant at certain areas, but especially so in saline-brackish and saline waters where there is no competition with the alien mosquito fish (*Gambusia holbrooki*). The fish that have survived in refugia will be the population sources for future expansion events. Recent developments and interventions in the lower reaches of the Vjosa river may exacerbate the negative effects on *Aphanius fasciatus*, which appears to be primarily impacted by competition with *Gambusia holbrooki* rather than by salinity fluctuations alone. Structural modifications to watercourses and channels could prevent killifish from accessing long-standing aquatic refugia in the region. A similar threat has been documented by Zogaris (2017) in the Zakaki marsh of Cyprus, where *Aphanius* populations were displaced by the seasonally abundant mosquito fish. In the Vjosa-Narta wetland complex, *Aphanius* populations persist in slightly brackish to saline inland marshes and lagoon ecosystems, and appear capable of tolerating freshwater conditions as well. However, available data suggest that brackish environments may be more favorable for reproduction. Following the complex of communicating channels, the lagoon, etc., they show higher abundance in small brackish pools in salt marshes and disperse among pools during winter-spring flooding events, but generally they are not considered good dispersers. *Aphanius* forms dense concentrations when waters shrink in spring and summer, while they can survive in very crowded conditions and in very warm waters.

Position of the lower Vjosa river and its delta on the ichthyology map of Albania and Europe

In the map of global ecoregions (Abell et al. 2008), the Vjosa river is part of the 420-South-east Adriatic Drainage. This freshwater ecoregion map is based on fish distributions and assemblage composition. However, the geomorphological complexity of the Vjosa basin and adjacent drainages makes precise delineation challenging. Albanian watersheds are defined as distinct river basins or isolated sub-basins, usually defined naturally by watershed boundaries. In Albania, there are several large, temporally independent river and lake systems. From north to south, they are arranged as follows: Drini (Ohrid-Drin-Skadar system including the Buna river), Mat, Ishëm, Erzen, Shkumbin, Seman (consisting of two major tributaries – Devoll and Osum), Vjosë (Aoos in Greece) river systems, several short rivers flowing from the Cika Mountains to the southernmost part of the Adriatic Sea and to the northernmost part of the Ionian Sea, the area around the Butrint lagoon (rivers Bistrice and Pavlo), and Lake Prespa (Shumka et al. 2023a).

Most of the above lakes and rivers belong to the catchment area of the Adriatic Sea and the southernmost areas to the slope of the Ionian Sea. Only a very small area in the northernmost part of Albania, in the Albanian Alps, is part of the Danube river basin. The area covered by this study corresponds to the Vjosa basin and, as stated above, lies at the Adriatic Basin. The river basins, delineated based on fish species richness and composition differences (Shumka et al. 2023a), are shown in Fig. 2. The data are derived from various published sources cited in Shumka et al. (2023a) as well as recent unpublished observations. The differences in geological settings and structures, and physicochemical characters of water in the different drainage basins enables different conditions for the development of fish communities within Adriatic watercourses. That has also enabled speciation processes (Economidis & Banarescu 1991). It is worth noting that basins differ because they have experienced distinct geological histories and environmental conditions. In the Vjosa, nine species (28%) are pelagophilic, five (16%) are phytophilic, and 15 (47%) are lithophilic. Taking feeding guilds into account, many species exhibit a variety of feeding tactics, making precise classification challenging. Following omnivorous feeding behavior (six species, 19%), the majority of fish species exhibit insectivorous (eight species, 25%) or insectivorous and herbivorous (eleven species, 34%) feeding behavior. As shown in Tab. 1, only two species (*Alosa fallax* and *Petromyzon marinus*) are solely piscivorous during their adult life stage.

Diversity of habitats of the lower Vjosa river and its delta system as a basis for development of fish communities

Following Schiemer (2000) the fluvial geomorphic processes provide the habitat diversity and the specific habitat conditions for characteristic species assemblages, and result in high levels of habitat diversity. Within this context, the local species richness and differences between habitats and consequently overall species richness of a river section is changing (Stanford et al. 2005). After Schiemer et al. (2020), the fish fauna is an important indicator for the ecological integrity of large river systems, as a broad spectrum of habitat conditions is required to fulfil the habitat needs of different ecological guilds in the course of their life cycle. In the Vjosa case, this issue has been elaborated in detail by Meulenbroek et al. (2018). Hence, the following habitats have been identified within the main river channel

(littoral zones), shallow runs, downstream connected and disconnected sidearms, erosion pools within the active channel, with and without aquatic macrophytes, and water bodies within the floodplain fed by hillside streams with clear water and macrophytes. Such braided reaches with moderate floodplain development in the case of the Vjosa represent highly unstable lotic to semi-lotic alluvial channels, and the dominating coarse material of bed and banks is transported and deposited by fluvial action (Schiemer et al. 2020). Very diverse and heterogeneous current and substrate patterns dominate the aquatic environment. The range of different morphological types within braided systems is very broad.

The clear spatial distribution patterns for the species (Meulenbroek et al. 2018) confirmed that sites within the main channel were dominated by *Barbus prespensis*, *Chondrostoma vardarense*, and *Gobio skadarensis*. *Anguilla anguilla* and *Squalius platyceps* were also commonly found. High numbers of *Oxynoemacheilus pindus* were caught in the shallow runs within the main channel accompanied mainly by *Gobio skadarensis* and *Barbus prespensis*. The downstream connected side arms still reflected species found in the running waters, though the most abundant species were *Alburnus scoranza* and *Squalius platyceps*. *Pachychilon pictum* and *Alburnoides aff. perspensis* additionally characterize this habitat type. The disconnected river side-arms and small erosion pools were mostly inhabited by *Alburnus scoranza*, *Squalius platyceps*, *Cobitis ohridana*, and *Pseudorasbora parva* and some individuals of the non-native *Gambusia holbrooki*. In the larger erosion pools within the active channel with a generally high cover of macrophytes and clear water situations, and in the waterbodies within the floodplain fed by hillside streams *Pelagus thespoticus*, *Alburnoides aff. Perspensis*, and *Gambusia holbrooki* were dominant, while *Pachychilon pictum*, *Alburnus scoranza*, *Squalius platyceps*, *Cobitis ohridana*, and *Pseudorasbora parva* were also represented (Fig. 2).

How did events in the geological past and in human history affect the fish community in the lower Vjosa river and its delta system?

Although numerous advanced methods are available to determine the age of a region and reconstruct the geological events that have shaped it, such data for the Vjosa river basin remain limited. The high biodiversity of Balkan rivers is a consequence of the region's geologic and paleoclimatic history, as well as the geophysical variety of inland water bodies (Bănărescu et al. 2004). Hence, during the Pleistocene, glaciers were restricted to mountain summits. The lowland areas provided refugia for the continental freshwater fauna and flora (Skoulikidis et al. 2009).

The Vjosa river and its tributaries (two of its main arms: Drino and Shushica) can be categorized as gravel-dominated, laterally active, anabranch rivers with large sediment yields, where the supply of bed loads is greater than the channel's actual transit capacity. This is evident, especially in the middle section of the river, where large gravel plains that can reach 2,000 meters in width are present and are traversed by numerous lateral and parallel rovers, oxbows, and side channels. The quick desertion of the main river channel during catastrophic flood events and the creation of new, parallel river channels in old floodplains are two further characteristics of laterally active, anabranch gravel bars.

From an ichthyo-geographical perspective, there are two major divisions that are known in the Balkans: the Ponto-Caspian and the Western Balkan. These divisions are biogeographically

distinct because mountain boundaries form old barriers to fish dispersal. The Western Balkan rivers are dominated by relatively depauperate but endemic-rich assemblages that have experienced long periods of isolation (Skoulidakis et al. 2009).

The Adriatic and Ionian subdivisions were considered to comprise a single ichthyogeographic region (the Southern Adriatic–Ionian Division) (Economidis & Banasescu 1991). Further on, Bianco (1986) discussed the issue that the Adriatic and Ionian drainages host different fish faunas, and proposed their separation. The Adriatic subdivision, delineated to the north by the Drin and to the south by the Aoos, is rich in endemic fishes (for faunistic descriptions see Crivelli et al. 1997; Shumka et al. 2023a).

The Ichthyofauna of the lower Vjosa river and its delta

Recent studies indicate that the lower Vjosa fauna comprises 34 species from 10 orders and 14 families. Cyprinidae is the most species-rich family, followed by Mugilidae (Shumka et al. 2018b). Salmonidae and Acipenseridae are represented by 2 species each. The remaining ten families are represented by a single species (Tab. 1, Figs. 3 and 4).

The lower river reach is populated by other species as: European eel (*Anguilla anguilla*), species of the family Mugilidae (*Mugil cephalus*, *Chelon ramada*, *Chelon salienes*, and *Chelon labrosus*), seabream (*Sparus aurata*), seabass (*Dicentrarchus labrax*), flatfish (*Platichthys flesus*), common sole (*Solea spp.*) etc.; while the resident species associated with saline water are numerically prevalent with the two species *Atherina boyeri* and *Aphanius fasciatus* showing presence and significance.

At least five non-native species have been reported from the basin: *Pseudorasbora parva*, *Oncorhynchus mykiss*, *Carassius gibelio*, *Ctenopharyngodon idella*, and *Gambusia holbrooki*. They were all introduced over the past 100 years as a consequence of human activity (Skoulidakis et al. 2009).

Following the Albanian Red List (MoE 2013), three species are endangered (*Acipenser naccarii*, *Acipenser sturio*, and *Aphanius fasciatus*) and two vulnerable (*Petromyzon marinus* and *Platichthys flesus*). The IUCN considers three species to be critically endangered (*Acipenser naccarii*, *Acipenser sturio*, and *Anguilla anguilla*) and additionally *Gobio skadarensis* is categorized as endangered.

The Bern Convention lists three species in Annex II (strictly protected fauna species) (*Acipenser naccarii*, *Acipenser sturio*, and *Aphanius fasciatus*) and two in Annex III (*Alburnoides aff. prespensis*, *Chondrostoma vardarensis*, *Pachychlione pictum*, and *Petromyzon marinus*) (Shumka et al., 2018; 2023a). There is a severe lack of knowledge concerning this river system compared to other systems in Europe, resulting in limited available data about these species and their population status. This means that more species than previously thought could be severely threatened.

To reach their spawning habitats or feeding grounds during different life stages, some fish exhibit migratory behavior. Some species undertake only short local movements to spawn (*Salmo fario*), whereas other species travel up to 10,000 kilometers in order to reach their

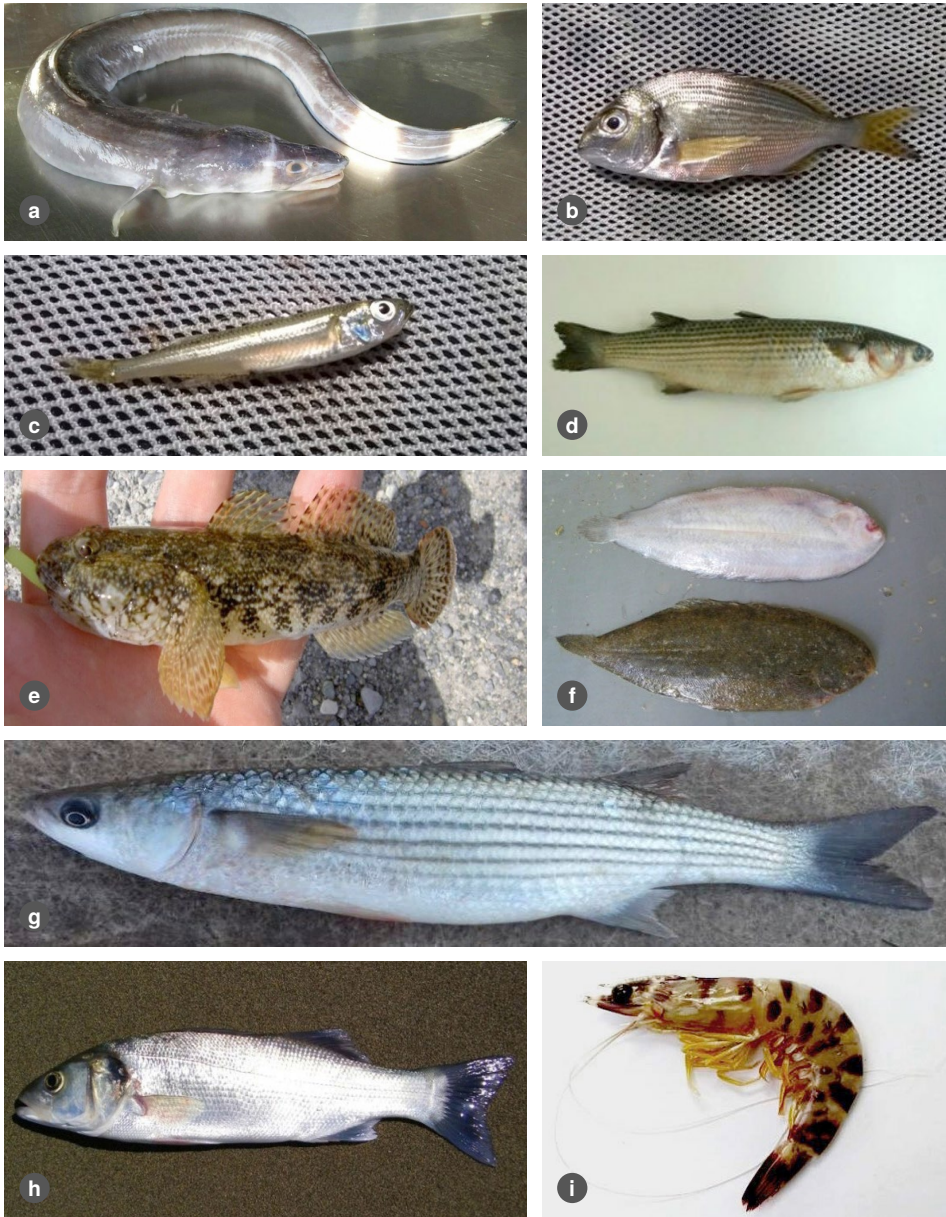


Fig. 3: Important fish species of the Vjosa delta and the lower reaches of the Vjosa river: (a) European eel (*A. anguilla*); (b) gilthead seabream (*S. aurata*); (c) sand smelt (*A. boyeri*); (d) thinlip grey mullet (*C. ramada*); (e) goby (*Gobius* sp.); (f) common sole (*S. vulgaris*); (g) flathead grey mullet (*M. cephalus*); (h) European seabass (*D. labrax*); (i) crustacean: caramote prawn (*M. kerathurus*) | **Abb. 3:** Wichtige Fischarten des Vjosa-Deltas und des Unterlaufs der Vjosa: (a) Europäischer Aal (*A. anguilla*); (b) Goldbrasse (*S. aurata*); (c) Mittelmeer-Ährenfisch (*A. boyeri*); (d) Dünnlippige Meeräsche (*C. ramada*); (e) Grundel (*Gobius* sp.); (f) Gewöhnliche Seezunge (*S. vulgaris*); (g) Dicklippige Meeräsche (*M. cephalus*); (h) Europäischer Wolfsbarsch (*D. labrax*); (i) Krebstier: Karamote-Garnele (*M. kerathurus*)

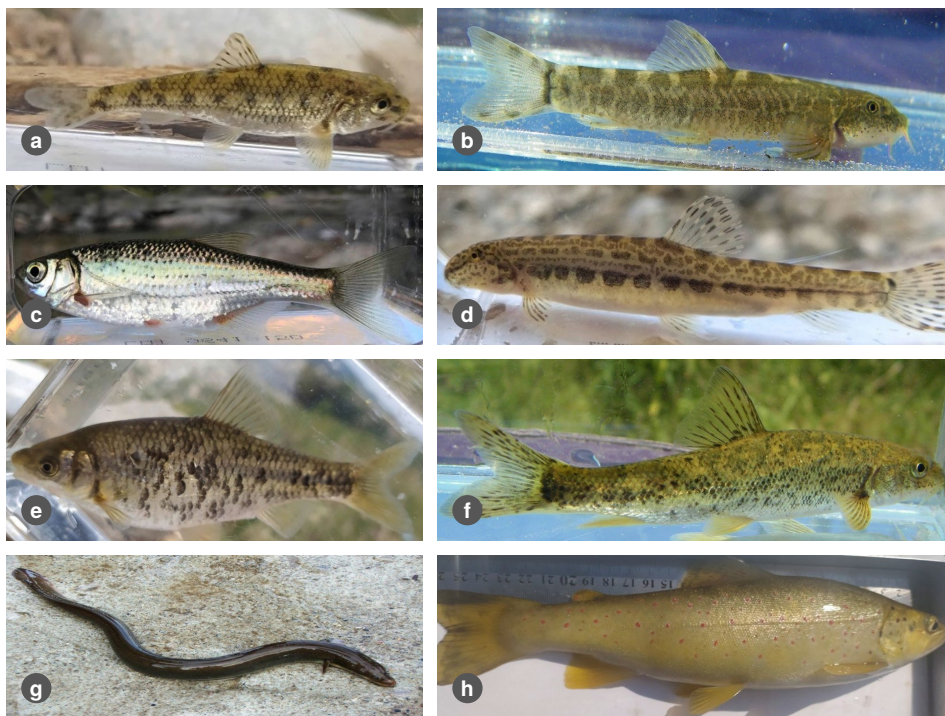


Fig. 4: Freshwater fish species occurring in the Vjosa river: (a) *G. skadarensis*; (b) *O. pindus*; (c) *A. cf. prespensis*; (d) *C. ohridana*; (e) *P. pictum*; (f) *B. prespensis*; (g) *A. anguilla*; (h) *S. farioides* | **Abb. 4:** Im Fluss Vjosa vorkommende Süßwasserfischarten: (a) *G. skadarensis*; (b) *O. pindus*; (c) *A. cf. prespensis*; (d) *C. ohridana*; (e) *P. pictum*; (f) *B. prespensis*; (g) *A. anguilla*; (h) *S. farioides*

spawning habitats (*Anguilla anguilla*) (Kottelat & Freyhof 2007). Concerning the native fish fauna of the Vjosa, migratory behavior has been described for: *Acipenser naccarii*, *Acipenser sturio*, *Anguilla anguilla*, *Alosa fallax*, *Atherina boyeri*, *Barbus prespensis*, *Chelon aurata*, *Chelon labrosus*, *Chelon ramada*, *Chelon saliens*, *Chondrostoma vardarense*, *Dicentrarchus labrax*, *Luciobarbus albanicus*, *Petromyzon marinus*, *Plathichthys flesus*, *Salmo farioides*, and *Squalius platyceps*, Thomson 1990; Bianco 1986; Kottelat & Freyhof 2007; Zupančič et al. 2010). These species are categorized by their average distance covered during migration in three groups, namely:

- **Sea-run species (Diadromous):** Showing a migration from saltwater to freshwater. (*Acipenser naccarii*, *Acipenser sturio*, and *Alosa fallax* are anadromous; *Chelon aurata*, *Chelon labrosus*, *Chelon saliens*, *Dicentrarchus labrax*, *Chelon ramada*, *Petromyzon marinus*, *Plathichthys flesus*) and freshwater to salt water or catadromous (*Anguilla anguilla*).
- **Long-distance migratory species/Potamodromous:** Covering average annual migration distances of 20 kilometers or more (e.g. *Barbus prespensis*, *Chondrostoma vardarense*, *Luciobarbus albanicus*, *Salmo farioides*, and *Onchorhynchus mykiss*).

- **Short-distance migratory species:** Covering average annual migration distances of less than 20 kilometers (*Alburnoides prespensis*, *Alburnus scoranza*, *Carassius gibelio*, *Cobitis ohridana*, *Gambusia holbrooki*, *Gobio skadarensis*, *Oxynoemacheilus pindus*, *Pachychlione pictum*, *Pseudorasbora parva*, *Squalius platyceps*, *Pelagus thespoticus*, *Atherina boyeri*, and *Aphanius fasciatus*).

Non-native fish species and threats to native Ichthyofauna

As stated above, there are five fish species that have been introduced into the Vjosa basin intentionally or accidentally. All alien species are not native at all to Albania: *Pseudorasbora parva*, *Oncorhynchus mykiss*, *Carassius gibelio*, *Ctenopharyngodon idella*, and *Gambusia holbrooki*.

Poljakov et al. (1958) provided the first information for Albania on the presence of only two introduced species, *Gambusia holbrooki* and *Cyprinus carpio*. Later, Rakaj (1995) reported the presence of a total of 20 non-native fish species for Albania. The ten-fold increase in the number of exotic species was due to the importing of species for aquaculture, especially East Asian cyprinids and several salmonids.

With the exception of *Lepomis gibbosus*, all remaining species found recently were included in Rakaj (1995), though two of the species mentioned by him and not found now are apparently incorrectly identified specimens of other introduced species: *Carassius carassius* and *Gambusia affinis*. Furthermore, *Misgurnus fossilis* and *Sabanejewia balcanica*, included in Rakaj (1995), are of uncertain status. Šanda et al. (2008) speculated that the record of *S. balcanica* in Rakaj (1995) could be due to misidentification of nontypical *Cobitis ohridana* specimens. The same could apply to *M. fossilis*. On the other hand, *M. fossilis* is well differentiated morphologically from *C. ohridana* (different number of barbels around mouth). Because many East Asian cyprinids were introduced to Albania, the presence of unintentionally transported East Asian *Misgurnus*, instead of *M. fossilis*, is also possible.

Several introduced species have become established in Albania, while the occurrence of *Oncorhynchus mykiss* probably results from escape from hatcheries, and that of *Hypophthalmichthys molitrix* from past introductions with no record of successful reproduction.

According to many local fishermen that were contacted, there are no recent records of most of the East Asian cyprinids *Hypophthalmichthys nobilis* (Richardson, 1845), *Ctenopharyngodon idella* (Valenciennes, 1844), *Megalobrama terminalis* (Richardson, 1846), *Parabramis pekinensis* (Basilevsky, 1855), nor of a few other species (*Thymallus thymallus* (Linnaeus, 1758), *Ameiurus melas* (Rafinesque, 1820), *Coregonus* sp.) reported in Rakaj (1995). Introductions of the above-mentioned taxa were most probably unsuccessful.

The introduction of non-native species is recognized as a major threat to native freshwater fish, particularly when combined with other stressors such as hydropower development, unsustainable water management (in terms of both quantity and quality), pollution, and eutrophication – all of which contribute to the ongoing decline in native fish populations (Piria et al. 2017). Although non-native species were not commonly observed across most

surveyed areas in Albania in the present study, they are notably widespread in the country's four major lakes. These systems host established populations of several invasive species, including *Cyprinus carpio*, *Carassius auratus*, and *Pseudorasbora parva*, the latter of which appears to be particularly abundant. In Prespa lakes two other introduced species, *Tinca tinca* and *Lepomis gibbosus*, have become established; while around Lake Ohrid the rearing and accidental release of *Oncorhynchus mykiss* continues virtually unchecked. Following current knowledge for Albania there are 24 non-native fish species (Shumka et al. 2023a).

How can Vjosa National Park contribute to fish recovery and persistence?

The natural special character and unique landscape, biological diversity, and other associated values of the Vjosa river has led to protection of this area at different levels – it is protected under national legislation as a national park; it is included within its lower part in the candidate list of Emerald (ASCI sites) and potential Natura 2000 network sites; IBA (Important Bird Area), etc. However, despite the various layers of protection and abundant natural resources, this area, like many others, has not been immune to the negative consequences of anthropogenic activity (Schiemer et al. 2018). The fragile aquatic ecosystems of the Vjosa river, particularly in its lower reaches and delta, are subject to numerous pressures, with the most evident impacts observed in the native fish populations.

According to Sovinc (2021), the concept of protecting wild rivers and their tributaries is grounded in the strict preservation of the entire active riverbed, while permitting traditional land-use practices – such as agriculture and grazing – to continue, provided they are managed at a subsistence level rather than on an industrial scale. This approach also envisions the Vjosa river valley as a prime candidate for the development of green, cultural, and recreational tourism. Such a model aligns closely with fish conservation objectives, as the preservation of habitat heterogeneity is essential for the survival of native species and the completion of their life cycles (Shumka et al. 2018b).

Conclusions

The Vjosa river, as a dynamic fluvial system, exhibits a distinct longitudinal continuum encompassing steep-gradient headwaters, braided and meandering middle reaches, and deltaic formations at its terminus. This geomorphological diversity supports high fish species richness and provides an essential migration corridor. However, potential hydromorphological alterations – such as embankment, channel straightening, and reservoir construction – pose significant threats to the ecological integrity of the system. These interventions would directly affect the structure and function of the delta, as well as reduce groundwater aquifer recharge.

Given that aquatic and riparian fauna – particularly native fish species – are increasingly threatened across many Albanian river basins, the implementation of effective conservation strategies is of critical importance. The lowland sections and deltaic areas of the Vjosa are especially vulnerable due to shifts in agricultural practices, rapid infrastructure development, expanding tourism, and large-scale modifications occurring in the headwaters. Consequently, environmental decision-making in the region must be approached with heightened sensitivity, prioritizing biodiversity conservation and the principles of integrated river basin management.

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***In situ* and *ex situ* conservation of the endangered plant species *Artemisia laciniata* (Asteraceae) in Austria**

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The aims of the present project were to reinforce the existing population of *Artemisia laciniata* (Asteraceae) in Austria's Neusiedler See – Seewinkel National Park (NP) and to implement *ex situ* conservation measures to support this effort. The plants growing in the slightly saline meadows of the NP represent the last remaining population of this critically endangered species in Europe. In 2015, only 11 individuals were known to exist.

Monitoring of the wild population was conducted, and early observations identified the mowing regime as a critical factor for the species' survival. The mowing management was optimised based on the artificial mowing experiments performed in garden beds at the University of Vienna. The results showed that cutting the plants back to 80 mm in mid-June could lead to about 25 % reduction in the number of plants developing generative stems and a 75 % decrease in the number of generative stems compared to the control group.

The attempt to activate the soil seed bank in an extinct field site was unsuccessful. However, sowing achenes and planting pot plants proved to be effective reinforcement measures. The survival rate of plantings reached up to 95 % after five years, and seedlings from achenes had a 20 % survival rate. However, the success was highly dependent on the location and its microhabitat.

By 2023 the *Artemisia laciniata* population has been stabilised with more than 270 plants on site, and achenes collected over three years are stored at the Millennium Seed Bank. While reintroduction protocols are now in place and the measures appear promising, it is important to continue monitoring to evaluate the long-term success of the plantings, particularly in light of global warming.

Kodým A, Pirker T, Kiehn M, Klaps M, Knickmann B, Schumacher F (2026) *In-situ-* und *Ex-situ*-Erhaltung der gefährdeten Pflanzenart *Artemisia laciniata* (Asteraceae)

Ziel des Projekts war die Stärkung der bestehenden Population von *Artemisia laciniata* (Asteraceae) im österreichischen Nationalpark (NP) Neusiedler See – Seewinkel und die Durchführung von *Ex-situ*-Erhaltungsmaßnahmen zur Unterstützung dieser Bemühungen. Die Pflanzen, die in den leicht salzhaltigen Wiesen der Zitzmannsdorfer Wiesen wachsen, stellen die letzte verbleibende Population dieser stark gefährdeten Art in Europa dar. Im Jahr 2015 waren nur noch 11 Exemplare bekannt.

Es wurde ein Monitoring der Wildpopulationen durchgeführt, und erste Beobachtungen ergaben, dass das Mähregime ein kritischer Faktor für das Überleben der Art ist. Das Mähmanagement wurde optimiert, basierend auf den künstlichen Mähexperimenten in Gartenbeeten an der Universität Wien. Die Ergebnisse zeigten, dass ein Rückschnitt der Pflanzen auf 80 mm Mitte Juni zu einer ca. 25 prozentigen Verringerung der Anzahl der Pflanzen, die Blütenstände entwickeln, und zu einer Verringerung der Anzahl der Blütenstände um 75 % im Vergleich zur Kontrollgruppe führt.

Der Versuch, die Samenbank im Boden an einem erloschenen Standort zu aktivieren, blieb erfolglos. Die Aussaat von Achänen und das Ausbringen von herangezogenen Topfpflanzen erwiesen sich jedoch als wirksame Maßnahmen zur Verbesserung der Populationsgröße. Die Überlebensrate der Anpflanzungen war nach fünf Jahren bis zu 95 %, während die Überlebensrate der Sämlinge aus Achänen bei 20 % lag. Der Erfolg hing jedoch stark vom Standort und seinem Mikrohabitat ab.

Bis 2023 konnte die Population von *Artemisia laciniata* mit mehr als 270 Pflanzen vor Ort stabilisiert werden, und die über drei Jahre gesammelten Achänen sind in der Millennium Seed Bank eingelagert. Obwohl nun die entsprechenden Protokolle vorliegen und die Maßnahmen vielversprechend erscheinen, ist es wichtig, das Monitoring fortzusetzen, um den langfristigen Erfolg der Anpflanzungen zu bewerten, insbesondere im Hinblick auf die Klimaerwärmung.

Keywords: conservation measures, Millennium Seed Bank, monitoring, mowing regime, national park, reinforcement.

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Introduction

Artemisia laciniata Willd. (Siberian wormwood) is a deciduous semi-rosette perennial with a growth height of 15 to 50 cm (with the generative stems). The generative stems are upright and carry numerous inflorescences. The main distribution area of *A. laciniata* is Central Asia (Fischer & Fally 2006), where it is common (Ellmauer 2005). In this part of the world, it occurs as a frequent companion of fresh, herbaceous larch forests or in aspen and birch forests, but also in meadows and meadow steppes (Jäger 1987).

The last natural occurrence of *A. laciniata* in Europe is found in Austria in the Zitzmannsdorf meadows at the Neusiedler See – Seewinkel National Park (Burgenland) (Kästner & Fischer 2011). The Zitzmannsdorf meadows have been part of the preservation zone of the NP since 1993 and are the largest contiguous meadow area in Burgenland, covering about 400 ha (Naturschutzbund Burgenland 2020). According to Fischer & Fally (2006), the nearest occurrence of *A. laciniata* to Austria is in southern Russia. In Europe, as well as in Austria, the status “critically endangered” applies (Niklfeld & Schratt-Ehrendorfer 1999; European Commission 2011; Schratt-Ehrendorfer et al. 2022). *A. laciniata* is listed as a priority species in Annex II and IV of the Habitats Directive (Council Directive 92/43/EEC 1992).

In the past, a second Austrian population was situated in Lasse (Lower Austria), but it became extinct in the 1960s. German populations in Saxony-Anhalt and Thuringia existed until around 1900 (Jäger 1987). The causes of extinction in Germany and Austria were probably habitat destruction and change, e.g. drainage, but also the collection of herbarium specimens seem to have contributed to the decline (Wendelberger 1959; Jäger 1987).

The Austrian population grows in a weakly saline meadow (Fischer et al. 2008; Kästner & Fischer 2011) where the reduced competitive pressure due to salinity may have allowed

the species to persist until today. The mowing regime of the meadows plays a key role in conservation efforts. As *A. laciniata* flowers from August to October (Hegi 1929; Jäger 1987; Fischer et al. 2008; Kästner & Fischer 2011), mowing must take place before the plants develop generative stems. In late autumn and winter, the meadows are too wet for bringing in mowing machinery. The window for mowing is further constrained by the fact that the meadows are an Important Bird Area (IBA) and protected as breeding grounds in springtime.

Over the previous years, protocols for the *in vitro* propagation and cryopreservation of *A. laciniata* have been developed (Kodym et al. 2018) and a population genetics study was conducted by the Research Group Plant Ecological Genomics of the Department of Botany and Biodiversity Research at the University of Vienna (Ovidiu Paun, unpublished data). This study showed that the population on the Zitzmannsdorf meadows, despite the low number of individuals, has a low inbreeding factor and high genetic diversity.

The aims of the present project were to maintain and reinforce the wild population of *A. laciniata* and to implement *ex situ* conservation measures. Since 2015 various conservation efforts have been carried out, with the main activities outlined in this paper: (a) monitoring of the natural population, (b) population expansion by sowing achenes and by planting, (c) attempts to activate the soil seed bank, (d) establishment of a mowing management, (e) expanding the living collection, and (f) storing seeds in the Millennium Seed Bank.

Materials & Methods

Monitoring of wild population

In 2015, at the onset of this project, only eleven individuals of *A. laciniata* were known at the original site, which covered an approximate area of 200 m². These plants are thus referred to as the “original stand”, as opposed to the new stand which was discovered only in 2018 (Fig. 1). All plants of the wild stands were labelled with numbered galvanised steel screws in the ground, in order to allow relocating with a metal detector. This was essential to quickly find and clearly identify individual plants in the field. The individual plants were additionally mapped using a GPS (SEPTENTRIO “Altus NR2”) with a position accuracy of less than 20 mm horizontally as well as vertically. New plant discoveries in following years have been marked and recorded in the same way. During regular monitoring, a GPS device (GARMIN Oregon 600) with positional accuracy ± 3 m was used to locate the sites.

The meadow surrounding the *Artemisia* plants was excluded from the farmer’s mowing activities, which happened once a year around June. However, the vegetation around the plants were cut with different tools including brush cutters, lawn mowers, grass clippers and a Stanley knife.

Vegetation surveys of the original stand, the new stand, the 8 Z plots, the *in vitro* 2018 site and the seed bank mound were carried out in 2017 or 2022. (Fig. 1) (Arge Vegetationsökologie und Landschaftsplanung, AVL, 1060 Vienna, Austria). The species nomenclature was based on Fischer et al. (2008) and the vegetation units on Mucina et al. (1993). The weather data for the nearest monitoring station in Podersdorf am See was retrieved from GeoSphere, Austria (<https://data.hub.geosphere.at>).

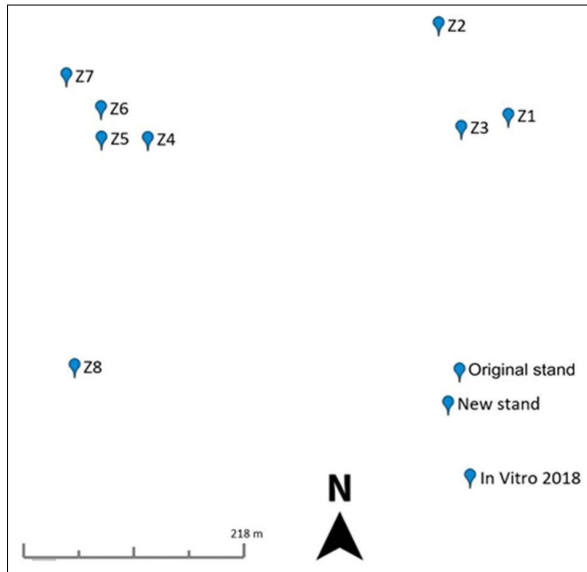


Fig. 1: Location map in the Zitzmannsdorfer Meadows, showing the wild populations of *Artemisia laciniata* (original stand known before 2018 and new stand discovered in 2018) and additional reinforcement stands (Z1-Z8 and the *in vitro* site) | **Abb. 1:** Standortkarte in den Zitzmannsdorfer Wiesen mit den Wildpopulationen von *Artemisia laciniata* (ursprünglicher Bestand, bekannt vor 2018 und neuer Bestand, entdeckt 2018) und zusätzlichen Verstärkungsbeständen (Z1-Z8, sowie der *In-vitro*-Standort)

Expansion of the population by means of sowing

Sowing into the original stand

Sowing of achenes was carried out on February 1, 2018 in a one square meter plot only a few meters away from the original stand. The vegetation of the plot was removed and the area refilled with fresh soil from nearby mole hills. Fruit stalks of the original stand from 2017 were crushed between fingers and spread out evenly. The material was pressed down and the area lightly covered with grass clippings for protection against drift and to keep the moisture. Later, wild carrot seedlings and upcoming thistles were removed as part of the maintenance.

A second sowing took place on December 18, 2020 with crumbled seed heads from the 2020 harvest. Three narrow strips were set up (100 cm × 20 cm) to reduce exposure to environmental elements.

Spring sowing into the new Z plots

Eight plots (6 × 6 m) were established in the larger area of the Zitzmannsdorf meadows (referred to as Z1-Z8, Fig. 1). A short hollow metal rod painted in red was hammered in at the east bottom corner of the plot, which can be located with a metal detector (BOSCH

digital locator “Truvo”). The corner point was mapped using two different GPS devices (GARMIN Oregon 600 and SEPTENTRIO). The sites were selected based on criteria of vegetation and soil moisture similarity with the original population and considering the presence of mole hills. Sowing took place on March 5, 2020. The achenes (five each) were sown into five molehills from previous years, as the sites were mostly free of other plants. Each sowing point was marked with a coloured wooden skewer, sticking out about 20 mm above ground. A map was also drawn.

Winter sowing into the new Z plots

On December 18, 2020, 10 achenes were sown at five sites in each of the eight Z plots. The vegetation was removed and the uneven ground filled with molehill soil before the sowing took place. A total of 400 achenes were used. The sites were marked as described in the spring sowing.

Expansion of the population through planting

In vitro-derived seedlings

In May 2018, a new additional large plot (appr. 14 × 14 m) was set up south of the original stand, where pot plants were planted (In Vitro 2018, Fig. 1). The plants were derived from *in vitro* germination. Achenes were harvested from the original stand in October 2017 and cultured *in vitro* in December following the protocol by Kodym et al. (2018). The germination rate was 31%. The rest of the achenes were either contaminated or did not germinate. The *in vitro* plants were acclimatised in the glasshouse. Three weeks before planting in the field, they were brought into a courtyard for hardening off.

On May 23, 2018, 88 seedlings were planted in four transects, each 10 meters long with 22 plants in a zig zag line. The dense vegetation was first removed for each site with a spade, refilled with soil from mole hills and compressed slightly. The distance between the transects was 1 m. All plants were watered after planting.

Beginning of August 2018, the plants were additionally watered due to persistent drought and heat. Over the coming years, the area was mown once a year and monitoring was carried out regularly.

Nursery raised seedlings

Plants from achenes (crop year 2019, original stand) were raised in the Botanical Garden of the University of Vienna, Rennweg, 1030 Vienna. Sowing took place on January 30, 2020. The achenes had been stored at room temperature until sowing. One half of the achenes was germinated frost-free in the cold house (7 °C minimum in winter), the second half in the outdoor bed (cold frame). The cold house plants were moved outdoors in a cold frame after pricking out in April.

The best developed 80 plantlets from both treatments were selected and planted on October 9, 2020 at the eight Z plots. Per plot, five plants each were placed in one- year-old molehills

(after one year they are flat and have settled down) and five in newly dug sites. At the new sites, holes were punched out with the help of a hollow spade (LIECO, Austria). Soil from surrounding molehills, outside the plots, was used to fill the holes. The plants were marked with a coloured wooden skewer.

Activation of seed bank

A. laciniata was discovered in the Zitzmannsdorf meadow in the early 1950s by Melzer (1952a, 1952b, 1952c) at the foot of a small mound, which presumably formed the remains of a former gun emplacement of World War II. Plants were last reported at this location in 1959 (Wendelberger 1959). The vegetation on and around the mound was partially removed in November 2017 in three transects approx. 0.5×5 m to activate the potential seed bank.

Mowing trials *ex situ*

A “mowing trial” was carried out in raised garden beds at the University of Vienna, Spittelau, 1090 Vienna in order to determine the latest possible mowing time for the future mowing regime on the Zitzmannsdorf meadows that allows plants to fructify. The trial was conducted twice over the span of 2020 and 2021 and included a total of 108 vital plants. Over eight weeks, twelve plants (randomised) were pruned back to 80 mm (= mowing height of the bar mower in the field) with secateurs every week. The eight-week pruning phase lasted from June 12, to July 31.

Subsequently, monitoring was carried out until October 2, 2020/ October 15, 2021. The number of generative stems per plant was recorded every week. In 2020, the height of plants was also measured on a weekly basis. Phenological changes (e.g. appearance of first generative stems, first flowering...) were also documented. At the end of October/beginning of November, the plants with seed heads were checked for the presence of achenes. As soon as one achene was found, this plant was rated as “achenes present”.

During the trial, the plants were only watered in particularly dry weather via irrigation hoses at a maximum of twice a week.

***Ex situ* conservation**

Living collection at the botanical garden

In 2006, a living collection was established at the Botanical Garden of the University of Vienna from achenes harvested 2005 from the Zitzmannsdorf meadows. At that time, the living collection comprised 20 seedlings. In the 2014 inventory, eleven genotypes were counted, by 2016 the number had decreased to ten.

The plants were grown in pots with a substrate consisting of one part T6 planting substrate for woody plants and perennials (KRANZINGER, Austria) and one part permeable special substrate (consisting of 10 parts Cocopeat, 10 parts bark humus, 3 parts compost, 3 parts sand, 2 parts lava, 6 parts pumice and 10 parts gravel). Pots were set into coarse sand within a cold frame so that any roots growing through the drainage holes can take up moisture

from the surrounding and remain undamaged during repotting. In summer, the plants are watered 1–2 times a week, but generally kept rather dry. They are not fertilised, but weeds are removed regularly.

An inventory of the living collection was carried out in 2020. The living collection was supplemented with plants raised at the Botanical Garden of the University of Vienna to widen the genetic pool in 2022.

Millennium Seed bank

Achenes from the years 2020, 2021 and 2022 were sent to the Millennium Seed Bank for long-term storage.

Results

Monitoring of wild population

In 2018, the number of known individuals in the original stand had risen from 11 to 14, while a “new stand” with eleven plants was discovered on April 19, 2018, just 25 m south of the original stand. The plants were remarkably large and vigorous with at least 20 shoots each (Fig. 2), spreading over an area of approximately 200 m². This part of the meadow had been cut regularly with a tractor trailed mower by the local farmers. Over time, more plants were discovered in both stands, but also two small plants in the old stand disappeared. Thus, a total of 35 individuals (19 original and 16 new stand) were known in September 2023.



Fig. 2: Vigorous *Artemisia laciniata* plants in the new stand discovered in 2018 | **Abb. 2:** Kräftige *Artemisia laciniata* Pflanzen des 2018 entdeckten neuen Standortes

Inspired by discovering another stand, a search for other populations described for the Zitzmannsdorf meadows by Kasy (1961) and Melzer (1955) was carried out. However, the descriptions of the locations were cryptic and no plants could be found.

As part of the regular monitoring of the original and new stand, the generative stems were counted (Tab. 1). In the years 2015 and 2016 only one generative stem was recorded at the original stand.

The number of generative stems per individual and the percentage of plants flowering was highly variable from year to year. The biggest difference though was seen between the

Tab. 1: Overview of the number of generative stems of the original and new stock (2017–2023). The date in brackets indicates the day of the count. The light grey shading indicates which individuals were already known that year. A hyphen means the individual could not be located on the day of observation. | **Tab. 1:** Übersicht über die Anzahl der Blütenstände des originalen und neuen Bestandes (2017–2023). Das Datum in den Klammern ist der Tag der Zählung. Die hellgraue Schattierung zeigt an, welche Individuen in diesem Jahr bereits bekannt waren. Ein Bindestrich bedeutet, dass dieses Individuum am Tag der Beobachtung nicht gefunden wurde.

		Number of generative stems						
Plant ID		2017 (10.11.2017)	2018 (20.07.2018)	2019 (6.11.2019)	2020 (30.10.2020)	2021 (4.11.2021)	2022 (31.10.2022)	2023 (16.10.2023)
Original stand	1	7	9	0	2	0	1	0
	2	4	2	0	0	0	3	3
	3	1	3	2	0	0	0	0
	4	0	1	0	0	0	0	0
	5	0	3	0	0	0	0	0
	6	0	0	5	0	0	0	0
	7	-	1	0	-	0	0	0
	8	4	7	9	6	4	4	1
	9	1	1	2	0	0	1	1
	10	0	1	2	0	0	0	1
	11	0	-	-	-	-	-	-
	12	0	-	4	0	2	0	0
	13	2	2	1	0	7	0	0
	14	0	0	-	-	-	-	-
	15		1	0	5	4	5	1
	16		3	0	0	1	3	0
	33				0	0	0	0
	34						0	0
	35						1	0
	36						0	0
	37							1
Subtotal		19	34	25	13	18	18	8

		Number of generative stems						
		2017 (10.11.2017)	2018 (20.07.2018)	2019 (6.11.2019)	2020 (30.10.2020)	2021 (4.11.2021)	2022 (31.10.2022)	2023 (16.10.2023)
New stand	17		1	0	1	0	0	3
	18		24	6	22	0	11	17
	19		33	17	66	3	22	12
	20		28	12	43	4	40	9
	21		11	25	45	2	14	26
	22		17	0	11	1	1	1
	23		2	20	21	0	2	3
	24		1	0	0	0	0	0
	25		8	0	0	0	1	0
	26		12	11	31	0	0	0
	27		39	2	7	1	0	2
	28			24	60	22	33	43
	29			2	13	1	5	0
	30			3	14	3	4	8
	31				0	0	3	1
	32				2	5	1	6
Subtotal		-	176	122	336	42	137	131
In total		-	210	147	349	60	155	139

Tab. 2: Average number of generative stems at the original and new stands for the years 2017–2023. The new stand was only discovered in 2018. | **Tab. 2:** Durchschnittliche Anzahl an Blütenständen des originalen und neuen Bestandes der Jahre 2017–2023. Der neue Bestand wurde erst 2018 entdeckt.

	2017	2018	2019	2020	2021	2022	2023
Original Stand							
% of plants flowering	46	86	50	20	33	39	31
Generative stems per plant	3.2	2.8	3.6	4.3	3.6	2.6	0.4
New Stand							
% of plants flowering	-	100	71	81	56	75	75
Generative stems per plant	-	16	12.2	25.8	4.7	11.4	8.2

original and the new stand. The new stand consisted of large, vigorous plants and produced more generative stems (on average 4.7 to 25.8 per plant) than the original stand (0.4 to 4.3) (Tab. 2). Not all generative stems carried achenes; e.g., in 2020, a quarter of the plants produced none, others however were bearing many fruits.

The vegetation surveys assigned the original stand to a rather dry formation of the *Succiso-Molinietum caeruleae* (Pannonian bluegrass-pipegrass meadow). It shows transitional

character to the Pannonic semi-arid grassland of the *Cirsio-Brachypodium pinnati*. The stand could be assigned to FFH-type 6410. Ecologically, it is an alternately moist mowing meadow with changing dominances of *Molinia caerulea* with approx. 22.5 % cover, *Brachypodium pinnatum* (8 %) and *Bromus erectus* (3 %). The area exhibits a slight browsing tendency, indicated by comparatively high cover values of *Peucedanum cervaria* (Korner & Staudinger 2018).

The new stand was also categorised as *Succiso-Molinietum caeruleae* and was dominated by *Molinia caerulea* (10 %), *Brachypodium pinnatum* (8 %) and *Scirpoides holoschoenus* (6 %). *Bromus erectus* was present with 4 %, *Peucedanum cervaria* was not found (Korner & Staudinger 2022).

Expansion of the population by means of sowing

Sowing into the original stand

In April 2018, two months after the sowing, the first *Artemisia* seedlings appeared, but were still difficult to identify. On June 8, the peak of germination was reached with 120 seedlings. It was noticeable that the seedlings germinated best along the edge of the plot, which provided partial cover. The number of plantlets dropped sharply to 29 by October 2019. From the original 120 seedlings, around 20 % seem to have been established as plants after five years. In April 2022 and 2023, 23 plants were counted, of which 12 were clusters. Since *A. laciniata* propagates vegetatively via rhizomes (Jäger 1987), it was very difficult to



Fig. 3: Seedlings in the year 2020 | **Abb. 3:** Sämlinge im Jahr 2020

distinguish between large individual plants or plants with multiple shoots. First flowering occurred two years after sowing. In 2022, a total of 20 generative stems were counted (Fig. 3).

From the 2020 sowing into three strips, a total of 29 seedlings were counted in April 2022 (14/11/4 per strip). By September 2023, 17 plants were present (7/5/5). They carried no generative stems.

Spring sowing into the new Z plots

In contrast to the preliminary sowing experiment from February 2018 near the original stand, sowing achenes across eight new Z plots in mole hills at the beginning of March 2020 was not successful. On April 28 and July 13, 2020, no seedlings of *A. laciniata* could be found. On October 9, 2020, one seedling was recorded (germination rate = 0.5 %). However, it did not survive.

A comparison of the rain data shows that the field conditions in 2018 were more favourable than in 2020 and 2021 (Tab. 3).

Tab. 3: Monthly mean air temperature and monthly precipitation of the measuring station “Podersdorf” – measuring point no. 7912, Operator: ZAMG (<https://data.hub.zamg.ac.at>) | **Tab. 3:** Mittlere monatliche Lufttemperatur und monatlicher Niederschlag der Messstation „Podersdorf“ – Messstation Nr. 7912, Betreiber: ZAMG (<https://data.hub.zamg.ac.at>)

	Mean air temperature [°C]			Precipitation [mm]		
	2018	2020	2021	2018	2020	2021
January	3.2	0.6	1.6	19	7	32
February	-0.4	6.5	2.5	30	8	19
March	3.2	7.0	5.8	40	30	1
April	15.5	12.0	9.0	20	3	21
Sum				109	48	73

Winter sowing into the new Z plots

From the 400 achenes sown mid-December 2020 into freshly dug holes in the Z plots, 94 (23.5 %) had germinated by May 21, 2021. On August 13, 2021, 26 seedlings (6.5 %) had established themselves. However, in July 2022 the number was reduced to 12, and further down to 3 in 2023. The surviving plantlets were still in a three-leave stage.

Expansion of the population through planting

In vitro-derived seedlings

Overall survival of the 88 *in vitro*-derived plantlets (Fig. 4) was 47 % after five years (Tab. 4). The pattern that has been showing over the years, has become more and more prominent:



Fig. 4: Hardened off *in vitro* plants, ready for planting | **Abb. 4:** Abgehärtete *in vitro* Pflanzen, bereit für die Ausspflanzung

Tab. 4: Survival rate and number of flowering individuals of the 88 *in vitro*-derived plants (May 2028) | **Tab. 4:** Überlebensrate und Anzahl der blühenden Individuen aus der *in vitro* Kultur (88 Pflanzen, Mai 2018)

Evaluation	plants alive	% survival	flowering
July 2018	88	100	-
Oct. 2018	86	98	3
Oct. 2019	72	82	47
July 2020	64	73	11
Oct. 2021	57	65	23
Sept. 2022	52	59	7
Sept. 2023	47	53	9

survival and vigour depended on the transect they were growing in. The lowest survival rates were recorded in transect 1, the highest in transect 4. The survival rates varied between 18 and 95 %. Plants started flowering in the first year of being planted out. In 2023, generative stems were only found in transect 3 and 4 (Tab. 5).

The vegetation survey identified three distinct vegetation types within the small plot (Korner & Staudinger 2022). In transect 1, both *Euphorbio verrucosae-Caricetum montanae* and *Filipendulo vulgaris-Brometum* were present. The boundary between the three vegetation types

Tab. 5: Survival rate of the *in vitro* plants and the number of generative stems per transect (September 2023) | **Tab. 5:** Überlebensrate der *in vitro* Pflanzen und Anzahl der Blütenstände pro Transekt (September 2023)

	plants alive	%	generative stems
Transect 1	4	18	0
Transect 2	7	32	0
Transect 3	15	68	3
Transect 4	21	95	7

Tab. 6: Vegetation types of the *in vitro* 2018 planting site | **Tab. 6:** Vegetationstypen auf der *In vitro* 2018 Fläche

Vegetation classification	Main species and their cover in %
<i>Euphorbio verrucosae-Caricetum montanae</i>	<i>Bromus erectus</i> 58, <i>Chrysopogon gryllus</i> 20
<i>Filipendulo vulgaris-Brometum</i>	<i>B. erectus</i> 60, <i>C. gryllus</i> 5, <i>Festuca pseudovina</i> 5
<i>Succiso-Molinietum</i>	<i>B. erectus</i> 60, <i>B. pinnatum</i> 6

ran diagonally across the plot, with a gradual increase of *Succiso-Molinietum*. Transect 4, which showed the highest survival, was entirely dominated by *Succiso-Molinietum*. The vegetation types and most common species are found in Tab. 6.

Nursery raised seedlings

After sowing achenes in the Botanic Garden of the University of Vienna on January 30, 2020, the first seedling was visible in the cold house on February 6, and over a month later, on March 10, in the outdoor bed. The seedlings from the cold house kept their head start and were pricked out on April 7, those in the outdoor bed on July 14 and August 10.

While the cold house conditions favoured fast germination and development (Fig. 5), the outdoor beds resulted in a higher germination rate. The average germination rate of achenes sown frost-free in the cold house was 47.3 % with a germination time of 1–2 weeks, in the outdoor bed 73.6 % with a germination rate of 5–6 weeks.

Survival in the eight Z plots was promising, although the number decreased steadily over the three years. In October 2023, 48 of 80 plants (60 %) had survived. The survival rate in the new holes (70 %) was better than in the molehills (50 %) (Tab. 7). A total of 40 generative stems was recorded. Various sites showed traces of animal activities from crows, moles, deer and hares. Marking the individual trial sites with environmentally friendly wooden sticks did not persist. Field mowing by the farmer with cutter bars and rakes removed most of them. Therefore, after one season, the locations were marked with bright coloured metal screws in the ground, which can be detected with a hand-held metal detector.

Two vegetation types were present – the *Succiso-Molinietum* and the *Euphorbio verrucosae-Caricetum montanae* (Tab. 8). The dominant plant in all plots was *Bromus erectus*, with

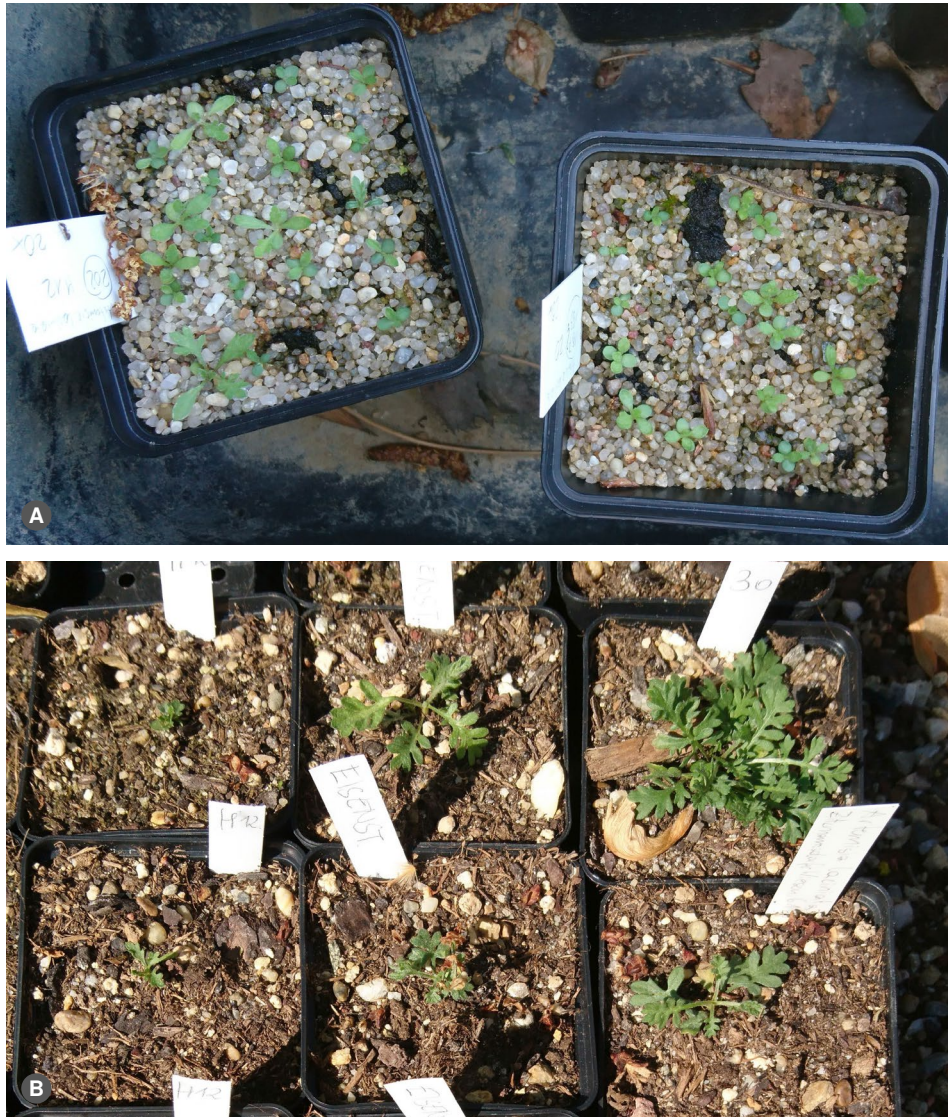


Fig. 5: Comparison of germination in the cold house and the outdoor bed. A: seedlings from the outdoor bed; B: pricked plants from the cold house (both photographed on 28.4.2020) | **Abb. 5:** Vergleich der Keimung im Kalthaus und Außenbeet. A: Sämlinge des Außenbeetes; B: pikierte Pflanzen des Kalt-hauses (beide Fotos aufgenommen am 28.4.2020)

a cover ranging from 30 % to 70 % (Korner & Staudinger 2022). The accompanying plants were grouped into dry, mesic and wetland species. No correlations could be made when trying to link survival of *A. laciniata* seedlings with the vegetation class or indicator species or their percentage cover. The obtained results were further influenced by animal disturbance and undifferentiated mowing.

Tab. 7: Survival percentages of the 80 cultivated plants in mole hills and new holes (planted Oct. 2020) | **Tab. 7:** Prozentuale Überlebensraten der 80 vorgezogenen Pflanzen in Maulwurfshügeln und neu gegrabenen Löchern (gepflanzt im Okt. 2020)

	molehills	new holes	total
Oct. 2020	95.0	97.5	96.3
May 2021	90.0	97.5	93.8
Aug. 2021	80.0	97.5	88.8
July 2022	67.5	82.5	75.0
Oct. 2023	50.0	70.0	60.0

Tab. 8: Comparison of survival percentages between new holes and molehills in the eight plots linked with the vegetation survey data (July 2022) | **Tab. 8:** Vergleich der prozentualen Überlebensraten zwischen neu gegrabenen Löchern und Maulwurfshügeln in den acht Standorten in Verbindung mit den Daten der Vegetationsaufnahme (Juli 2022)

Plot	Vegetation type	Main accompanying species (with > 5 %)	Cover % dry:wetland plants	Survival %		
				new holes	molehills	total
Z1	<i>Succiso-Molinietum</i>	<i>Bromus erectus</i> 60, <i>Festuca pseudovina</i> 6	67:7	60	100	80
Z2	<i>Succiso-Molinietum</i>	<i>B. erectus</i> 40, <i>F. pseudovina</i> 10, <i>Colchicum autumnale</i> 6	67:1	100	40	70
Z3	<i>Euphorbio verrucosae- Caricetum montanae</i>	<i>B. erectus</i> 70	83:4	100	100	100
Z4	<i>Euphorbio verrucosae- Caricetum montanae</i>	<i>B. erectus</i> 47, <i>Briza media</i> 6	82:3	80	60	70
Z5	<i>Euphorbio verrucosae- Caricetum montanae</i>	<i>B. erectus</i> 30, <i>Chrysopogon gryllus</i> 22, <i>Brachypodium pinnatum</i> 8	80:9	60	60	60
Z6	<i>Euphorbio verrucosae- Caricetum montanae</i>	<i>B. erectus</i> 40, <i>F. pseudovina</i> 10, <i>Centaurea scabiosa</i> 6	69:7	100	60	80
Z7	<i>Euphorbio verrucosae- Caricetum montanae</i>	<i>B. erectus</i> 66, <i>C. scabiosa</i> 6	84:1	60	40	50
Z8	<i>Succiso-Molinietum</i>	<i>B. erectus</i> 64	72:13	100	80	90

Activation of seed bank

The seed bank trial at the site was started in November 2017. Throughout 2018 many seedlings emerged, especially of thistle species, but none of *A. laciniata*. At the last monitoring in July 2020, the area was partly overgrown again and no seedlings or rosettes of *A. laciniata* could be found.

The vegetation survey could not assign a clear vegetation unit to the quite heterogeneous area. It corresponds most closely to the *Filipendulo vulgaris*-*Arrhenatheretum*. *Arrhenatherum*

elatus covered approx. 25 %, a clonal stand of *Carex riparia* and numerous disturbance indicators were recorded.

Mowing trials *ex situ*

In 2020 and 2021 artificial mowing experiments were carried out in the garden beds of the University of Vienna (Fig. 6). Height measurements were conducted during 2020. The average height of the rosette plants in the control group (no mowing) increased continuously until August 7 due to the growth of the generative stems, and reached the maximum at 556 mm. The plants cut back during weeks 1–3 reached an average height of over 300 mm, while those cut back in weeks 4–6 grew over 200 mm. However, plants cut back in weeks 7 and 8 reached less than 200 mm. This was reflected in the height of the generative stems, which were shorter in the treatments than in the control group.

The first generative stem in the control group appeared on June 19 with the proportion of flowering plants steadily increasing until July 3, when 11 out of 12 plants had generative stems. The flowering period in the control group lasted from August 21 to October 2. For plants cut back during weeks 1 to 6, flowering began one week later, on August 27, while those cut back in weeks 7 and 8 started flowering two weeks later, on September 4. Despite the delayed start, all generative stems eventually bloomed, regardless of when they were produced.

In 2021, the flowering period shifted forwards by about one week as compared to 2020 (Tab. 9). The majority of the plants (10 out of 12) in the control group already had generative



Fig. 6: Plants of the control group and experimental groups in one of the garden beds of the mowing experiment | **Abb. 6:** Pflanzen der Kontrollgruppe und Versuchsgruppen in einem der Gartenbeete des Mähversuches

Tab. 9: Comparison of flowering in the control group in 2020 and 2021 | **Tab. 9:** Vergleich der Blüte in der Kontrollgruppe im Jahr 2020 und 2021

	2020	2021
First generative stem	19. June	before 11. June
Flowering period	21. Aug. – 2. Oct.	27. Aug. – 7. Oct.
Main flowering period	27. Aug. – 18. Sept.	3. Sept. – 10. Sept.
First flowers fading	18. Sept.	10. Sept.

Tab. 10: Differences in flower production between the control group and the eight experimental groups (12 plants per group, gs = generative stems) | **Tab. 10:** Unterschiede in der Blühproduktivität zwischen der Kontrollgruppe und den acht Versuchsgruppen (12 Pflanzen pro Gruppe, gs = generative stems = Blütenstände)

		2020			2021		
		Plants with generative stems		No of gs	Plants with generative stems		No of gs
Control		11	92 %	80	10	83 %	145
Cut back	Week 1 (11.6.21)	8	67 %	18	10	83 %	108
	Week 2 (18.6.21)	8	67 %	18	9	75 %	80
	Week 3 (25.6.21)	6	50 %	19	8	67 %	33
	Week 4 (02.7.21)	6	50 %	13	9	75 %	30
	Week 5 (09.7.21)	5	42 %	8	9	75 %	35
	Week 6 (16.7.21)	5	42 %	9	6	50 %	14
	Week 7 (23.7.21)	2	17 %	3	5	42 %	10
	Week 8 (30.7.21)	2	17 %	7	6	50 %	10

stems at the start of the mowing trials on June 11. Over time, the number of generative stems increased, while the number of plants with generative stems remained the same. The flowering period of the control group extended from August 27 to October 7. For the plants that were cut back during weeks 1 to 2, the flowering time was similar to the control group. For weeks 3 to 8, the start of flowering was one week later, on September 3. Again, all generative stems came into flower.

The number of plants with generative stems and the total number of generative stems until mid-September, the end of the main flowering season, are presented (Tab. 10). In 2020, 92 % of the plants in the control group developed generative stems. The later the “mowing” took place, the fewer plants produced generative stems. Weeks 1 and 2, weeks 3 and 4, weeks 5 and 6 and weeks 7 and 8 gave similar results. The number of generative stems produced depended on the time of cutting. Cutting in mid-June had a major impact, resulting in 27 % fewer plants with generative stems and 78 % fewer generative stems compared to the control group. In 2021, a similar overall trend was observed, although the harm was less.

Achenes in the control group were produced in 10 out of the 11 flowering plants (91 %) in 2020. In the experimental group, 36 out of 42 flowering plants (86 %) had produced achenes. In 2021, achenes were found in 8 out of 10 flowering plants (80 %) in the control group, and in 54 out of 62 flowering plants (87 %) in the experimental groups.

***Ex situ* conservation**

Living collection botanical garden

In the 2020 inventory, the ten genotypes from 2016 were still present, in some cases with multiple copies, as they had been propagated by division. Twelve new genotypes, derived from propagation of field-collected seed material, were added. The collection now comprises 22 genotypes.

Seed bank Millenium Seed Bank

Achenes from the years 2020, 2021 and 2022 are stored under the accession numbers 33806, 33807 and 33808 in the Millennium Seed Bank.

Discussion

In 2015, the population of *Artemisia laciniata* in the Zitzmannsdorfer meadows consisted of just eleven known plants. As of October 2023, the known population has grown to 273 individuals and is no longer confined to a small, vulnerable area. Of these 273 plants, 35 belong to the wild population, while 238 have been planted (195) or sown (43), keeping in mind that this paper here is limited to the key propagation activities.

In the initial phase, achenes could only be harvested from the original stand, which were weak and had very low production. This scarcity of seeds led to early attempts of applying *in vitro* culture. However, the discovery of the new stand with vigorous plants marked a turning point, offering new opportunities for conservation and propagation efforts. The sighting of a new stand in April 2018 highlights how easily *Artemisia laciniata*, as a rosette plant, can be overlooked in the meadow. The best time to spot plants is in spring (April), when the rosettes have sprouted, displaying a silvery hue, and other vegetation is not yet fully developed. Despite being in close proximity to the known stand, these individuals, some of them quite large, had remained unnoticed by excursion leaders, botanists and rangers. Attempts to activate the seed bank of a known extinct site were unsuccessful. Efforts to locate the populations described in old references for the Zitzmannsdorf meadows (Melzer 1955; Kasy 1961) were equally unsuccessful due to vague descriptions and the vast areas they referenced. This underlines the importance of providing GPS data to the National Park and using markers such as screws to ensure that future generations can accurately identify and distinguish wild populations and planting sites.

Artemisia laciniata requires small open spaces free from competing vegetation for successful germination and establishment, conditions that today are largely absent in the dense meadows. Small-scale soil disturbances created by mole activity provide openings for colonization, in particular for weak light competitors. Mole hills are very common in our experimental

area, but they did not provide suitable conditions for *A. laciniata*. To expand the wild population, two methods were employed: sowing of achenes and planting seedlings. Eight additional plots were established across the meadows to ensure that the plants are no longer confined to small, vulnerable areas. These plots were grouped together to facilitate pollen exchange. It became apparent that germination success is highly dependent on the micro habitat and soil moisture. The sowing within the 1 m² open area revealed that the achenes preferably germinated at the edges, where they benefited from the protection of some surrounding vegetation, such as grasses, while still being in relatively open conditions. Freshly dug small holes in the meadow also provided some protection from the weather and from animals and provided a micro climate suitable for germination. In contrast, achenes sown on old molehills with loose soil were highly exposed, leading to fast drying out of open soil and disturbance by animals like moles, crows, deer and hares. As no seedlings were observed on the molehills, it appears that these open conditions prevented successful germination and/or early stage establishment of plants. The same pattern was also observed with plantings: plants in freshly prepared sites had a higher survival rate than those on old molehills.

Sowing worked well near the original and new stand, but not in the more distant sites. Generally, planting out had a much higher success rate than direct sowing of achenes, although this method is more costly and time-consuming. Germination and cultivation of *A. laciniata* was very effective under protected nursery conditions, when seed were sown at the end of January, both in the cold house and in outdoor beds. This supports Kasy's (1978) observation that *A. laciniata* can be easily propagated from achenes.

A comparison of the field performance of *in vitro*-derived plants and nursery-raised plants revealed that their survival rates were identical after one summer, both at 98 %. However, a suitable location appears to be a highly critical factor just like in seed sowing. A noticeable gradient in survival was observed in the *in vitro*-derived plants, likely influenced by varying soil conditions affecting plant development. Salinity in particular may play a significant role, prompting plans for future soil sampling. Although the vegetation cover varied across the transects, no correlation was found with successful establishment of plants.

Implementing an appropriate mowing regime is crucial for the long-term conservation of *A. laciniata*. The positive impact of mowing on the plant's vegetative growth became apparent, when a new stand was discovered in 2018. These plants, which were included in the farmer's regular summertime mowing, grew large and vigorously. In contrast, the original stand, which had not been regularly mown for an extended period to protect achene production, consisted of weak plants. The difference in vitality of the plants was also reflected in reproduction, with the new stand to produce the majority of achenes. Consequently, a regular mowing regime has been introduced in recent years for the original stand, but the effects are yet to be seen.

The mowing trial conducted in the garden of the University of Vienna showed that summer mowing significantly reduced the number of flower heads. The trial was conducted to develop an effective mowing regime for the Zitzmannsdorfer meadows without incurring long travel distances and harming natural seed production. The flowering period in 2020 and 2021, from mid-August to early October, closely aligned with the flowering period from August to October reported in the literature (Kästner & Fischer 2011). In both

experimental years, the phenology of the garden plants mirrored that of the wild population. The experiment clearly demonstrated that mowing should not occur too late, as it would lead to a reduction in the number of plants with generative stems, the total number of generative stems and their length. Nevertheless, plants with flower heads, in both control and experimental groups, produced ripe achenes by late October to early November. Additionally, *A. laciniata* was found to tolerate cutting back to ground level, quickly sprouting back afterward.

The optimal mowing period for *A. laciniata* is between November and March/April. However, autumn and winter mowing is only possible in a small time window, due to wet soil conditions, making it difficult to bring in mowing equipment. On the other hand, mowing in spring and early summer is also not feasible, as the Zitzmannsdorfer meadows are designated as an Important Bird Area (IPA) (Dvorak 1995). For example, the meadows are a nesting site for the Eurasian curlew (*Numenius arquata*) (Dvorak et al. 2017), a species vulnerable in Europe and endangered in Austria. The curlew's breeding season extends from April to June (Ulmer et al. 2012). Notably, the breeding population in the Zitzmannsdorf meadows tripled between 1991 and 2011, partly contributed to the practice of late mowing (Dvorak et al. 2011).

Hand mowing, which was partially utilized during the project, is too costly for the long-term maintenance of the whole area, but may be possible when limited to the wild stands and selected plots. To simplify the mowing regime, it may be advantageous to completely omit mowing in individual strips for a year and alternate this practice annually. This approach would allow the plants to reach full fructification every other year and would also be beneficial for other plants with late seed set, and for animals, like over-wintering insects, eggs and larvae (Unterweger et al. 2018). The risk of a hay ball being stored on the plot or the tracks of the tractor running across remains a big concern.

Since 2006, a living collection of *A. laciniata* has been maintained in the Botanical Garden of the University of Vienna, safeguarding a significant portion of the genetic variation of the original population (unpublished data from the Research Group Plant Ecological Genomics, Ovidiu Paun, University of Vienna). Nevertheless, the species cannot be considered fully secured and there are plans to further expand the *ex situ* collection in the near future in order to encompass the entire genetic spectrum. Additionally, storing achenes in the Millennium Seed Bank from the wild population was on the agenda to minimise the risk of genetic loss. This is particularly important because it is known that species can adapt to cultivation conditions, which might result in the loss of adaptations necessary for survival in its natural habitat (Ensslin & Godefroid 2019).

Despite all the progress made, it is crucial to closely monitor the wild population and its reinforcement plantings in the coming years, incorporating observations into the ongoing adjustment of conservation measures. Natural spontaneous germination has not yet been observed, but would be essential for sustainable conservation. Additionally, climate change poses a significant threat to the species' vitality due to rising temperatures and increased drought. As a result, assisted migration to wetter locations may need to be considered to ensure the long-term survival of the species.

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First insights into lichen symbiont associations along a successional gradient in the glacier forefield of Ödenwinkelkees (Hohe Tauern, Austria)

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Although lichens play a central role in primary succession, they have so far been largely overlooked in ecological research on glacier forefields. This study presents the first molecular assessment to investigate association patterns of dominant lichen symbionts along a succession gradient in the glacier forefield of the Ödenwinkelkees (Hohe Tauern, Austria).

In a pilot study, lichen diversity and coverage was assessed across 11 permanently marked 1×1 m plots of the Ödenwinkel Research Platform, spanning ~225 years of deglaciation. Dominant lichen symbionts (mycobiont [fungus], photobiont [algae]) were molecularly identified using the classic barcode marker ITS and lichen cover was quantified from rectified top-view images. Assembly- and community patterns were explored using network- and multivariate statistics. A hump-shaped pattern of species richness was observed, peaking at ~100 years since deglaciation. Rock dwelling lichens dominated early stages, while soil dwelling species increased after ~46 years and prevailed at intermediate ages (mean coverage ~36%). Photobiont identity appeared to mediate mycobiont ecological range, with generalist fungi associating with multiple algal partners. Field assessable groups effectively indicated successional stage, and the mean thallus area of yellow *Rhizocarpon* spp. emerged as a promising proxy for terrain age.

This study highlights lichen community turnover and photobiont-mediated filtering along primary succession and provides a basis for future molecular and image-assisted lichenological research in alpine environments.

Gindorf S, Ruprecht U (2026) Erste Einblicke in die Assoziationsmuster der Symbiosepartner von Flechten entlang eines Sukzessionsgradienten im Gletschervorfeld des Ödenwinkelkees (Hohe Tauern, Österreich)

Obwohl Flechten eine zentrale Rolle in der Primärsukzession einnehmen, werden sie in der ökologischen Forschung zu Gletschervorfeldern bislang kaum berücksichtigt. Diese Studie präsentiert erstmals mit molekularen Methoden die Assoziationsmuster der dominanten Flechtensymbionten entlang eines Sukzessionsgradienten im Gletschervorfeld des Ödenwinkelkees (Hohe Tauern, Österreich).

In einer Pilotstudie wurden Flechtenvielfalt und -bedeckung auf 11 permanent markierten 1 × 1 m großen Parzellen der Research Platform Ödenwinkel untersucht, die ~225 Jahre seit der Entgletscherung abdecken. Die dominante Flechtensymbionten (Mykobiont [Pilz], Photobiont [Alge]) wurden mit Hilfe des klassischen Barcodemarker ITS molekular identifiziert und die Bedeckung wurde aus orthorektifizierten Bildaufnahmen quantifiziert. Gemeinschaftsmuster wurden mithilfe von Netzwerk- und multivariater Statistik analysiert.

Die Artenvielfalt folgte einem unimodalen Muster mit einem Höhepunkt etwa 100 Jahre nach der Entgletscherung. In frühen Stadien dominierten steinbewohnende Flechten, während bodenbewohnende Arten nach ~46 Jahren zunahmen und in mittleren Stadien vorherrschten (mittlere Bedeckung ~36 %). Die Identität des Photobionten schien das ökologische Spektrum des Mykobionten zu beeinflussen, wobei Generalisten mit mehreren Algenpartnern assoziiert waren. Feldbestimmbare ökologische Gruppen erwiesen sich als effektive Indikatoren für das Sukzessionsstadium, und die gemittelte Thallusfläche gelber *Rhizocarpon*-Arten zeigte Potenzial als Indikator des Moränenalters.

Diese Studie untersucht die Dynamik von Flechtengemeinschaften sowie die Assoziationen dominanter Symbiosepartner entlang eines Gradienten und liefert damit eine Grundlage für ein besseres Verständnis von Sukzessionsprozessen genauso wie für zukünftige molekulare und bildbasierte Untersuchungen.

Keywords: saxicolous lichens, terricolous lichens, successional gradient, chronosequence, lichen symbionts, photobiont guilds, glacier forefield, primary succession.

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Introduction

Accelerating climate change is causing the rapid melt of glaciers in the European Alps (Cannone et al. 2008; Roe et al. 2017). In glacier forefields, the retreating glacier tongue successively uncovers fresh terrestrial habitat that becomes available for *de novo* colonization by a wide range of taxa. This process creates a predictable gradient of environmental conditions along which primary succession unfolds, known as the successional gradient (Miller & Lane 2019), making glacier forefields excellent ‘natural laboratories’ to study ecosystem development and species assembly along chronosequences (Bradley et al. 2014; Junker et al. 2021; He et al. 2023).

Succession in glacier forefields typically follows a predictable pattern, which can be studied using a space-for-time substitution approach (Lovell et al. 2023). As distance from the glacier front increases, so does the age of the substrate, offering a proxy for temporal development. The community dynamics in glacier forefields are generally shaped by two main mechanisms: i) directional replacement of communities composed of only few pioneer species and ii) the directional accumulation of species along the successional gradient leading to a nested community structure (Nascimbene et al. 2017).

While the successional dynamics of vascular plants and many cryptogamic organisms in glacier forefields are relatively well studied (e.g. Faegri 1934; Favero-Longo et al. 2012; Erschbamer & Caccianiga 2016; Schumann et al. 2016; Junker et al. 2021), much less is known about the successional dynamics of lichens, particularly the interactions of their symbiotic partners along chronosequences. The symbiotic associations consist of heterotrophic fungi (mycobionts) and photosynthetic microalgae or cyanobacteria (photobionts). Most mycobionts belong to the Ascomycota, with a smaller fraction (~2%) to Basidiomycota (Lumbsch & Leavitt 2011). Approximately 85% of lichens associate with green algae, 10% with cyanobacteria, and 3–4% with both partners (Sanders & Masumoto 2021). Photobiont associations are often variable: one mycobiont may associate with different photobionts, sometimes even from distinct genera, depending on environmental context (Perez-Ortega et al. 2012; Wagner et al. 2021). These associations are also commonly structured in so-called photobiont-mediated guilds – groups of mycobionts ecologically connected through their use of the same photobiont pool (Rikkinen 2007; Duran-Nebreda & Valverde 2022).

Lichens are renowned pioneer organisms on newly exposed substrates (e.g. Türk & Erschbamer 2010; Favero-Longo et al. 2012; Wietrzyk-Pelka et al. 2018) contributing to stabilization, erosion resistance and fertilization in soil formation processes (Büdel & Colesie 2014; Ruprecht et al. 2014; Zavarzina et al. 2019). Despite their ecological relevance, lichens are often overlooked in successional studies, which traditionally emphasize vascular plants or microbial communities (e.g. Junker et al. 2021).

Many lichenological studies in glacier forefields have aimed to estimate moraine age using the thallus size of *Rhizocarpon* species with yellow thalli – commonly referred to as “yellow rhizocarpons” (e.g. Mottershead & White 1972; Proctor 1983; Garibotti & Villalba 2009; Loso et al. 2014). This approach, known as lichenometry, is based on the assumption that the largest thalli on surfaces of unknown age share comparable colonization histories, growth rates, and mortality dynamics with those on dated reference surfaces, allowing terrain age to be inferred after appropriate calibration (Armstrong 2016). However, the fundamental assumptions underlying lichenometry have long been debated. For instance, apparently large thalli may represent the coalescence of several individuals or may have been displaced by geomorphic processes such as rockfall, thereby challenging the reliability of size-based age estimates (Osborn et al. 2015). These limitations highlight the potential of alternative, statistically robust approaches to linking lichen growth patterns with moraine age, such as analyses based on mean thallus size rather than single largest individuals.

The comparatively few studies focusing on lichen diversity in glacier forefields have primarily addressed the visible fungal component of the lichen thallus, with only limited attention given to photobiont identity and dynamics (e.g. Türk & Erschbamer 2010; Favero-Longo et al. 2012; Nascimbene et al. 2017;). Nevertheless, recent molecular approaches have begun to reveal patterns of symbiont turnover along environmental gradients. For example, Beck et al. (2019, 2023) demonstrated shifts in lichen symbiont associations along Antarctic chrono sequences, highlighting the ecological role of photobionts in shaping lichen community assembly. More broadly, the composition and turnover of mycobiont–photobiont associations can reflect environmental filtering and symbiotic specificity (Blaha et al. 2006; Dal Grande et al. 2018), and such turnover may follow predictable trajectories along environmental gradients (Rolshausen et al. 2020, 2023). Together, these findings suggest that generalist mycobionts may respond to environmental variability by associating with different photobionts across conditions, thereby expanding their ecological niche through an enlarged “mutualistic niche” (Peay 2016).

In glacier forefields, Favero-Longo et al. (2012) described three major stages of cryptogam succession: pioneer assemblages within decades, intermediate stages after ~30–40 years, and a climax stage in the oldest terrain. These shifts often reflect increasing habitat stability and resource availability. While the pioneer assemblages consist mainly of saxicolous (rock dwelling) lichens, terricolous (soil dwelling) lichens generally increase in abundance and coverage from the intermediate stages following a general trend of increasing lichen species richness with time of deglaciation associated with changes in community structure (Türk & Erschbamer 2010; Favero-Longo et al. 2012; Nascimbene et al. 2017; Wietrzyk-Pelka et al. 2018).

Although molecular techniques such as ITS sequencing have revealed cryptic diversity among dominant symbiotic partners in lichens and challenged classical views of the specificity of mycobionts to their photobionts along climate gradients (Nelsen & Gargas 2009; Kraichak et al. 2015; Muggia et al. 2018; Ruprecht et al. 2020; Wagner et al. 2021) no studies have so far applied molecular tools for lichenological studies in glacier forefields. Traditional morphological identification of lichen symbionts – especially of crustose lichens from families such as Lecideaceae – is notoriously difficult due to their reduced

and often convergent phenotypic traits (Ruprecht et al. 2020). As a result, the use of molecular tools has become indispensable for accurate species delimitation in lichenological research (Bickford et al. 2007; Lumbsch & Leavitt 2011). DNA-based methods – such as probabilistic phylogenetic reconstruction or DNA barcoding using ITS markers – allow for reliable identification of both mycobionts and photobionts, even in morphologically cryptic taxa (Ruprecht et al. 2020). The ITS region has emerged as the most robust universal barcode for myco- (Yahr et al. 2016) as well as photobiont (Ruprecht et al. 2014; Muggia et al. 2020) identification. These approaches are especially critical in ecological settings like glacier forefields, where many lichen individuals are early-successional pioneers with underdeveloped, cryptic morphology and potentially dynamic symbiotic associations. By applying molecular techniques to both symbiotic partners, it becomes possible to uncover fine-scale patterns of biodiversity, community turnover, and specificity that remain hidden to morphology-based approaches alone.

In this study, we investigated the diversity, distribution and coverage of lichens along a well-defined successional gradient in the glacier forefield of the Ödenwinkelkees (Hohe Tauern National Park, Austria). We investigated 11 representative plots along the gradient (2008–1797 years) of the Research Platform Ödenwinkel, which comprises 140 permanent plots along the chronosequence and offers extensive ecological and environmental data for comparison (Junker et al. 2020), by assessing (1) the diversity of dominant lichen symbionts in the glacier forefield, (2) the associations of dominant symbiotic partners at different successional stages using network statistics and (3) the relationship between moraine age and mean thalli size of yellow *Rhizocarpon* individuals.

Material and Methods

Study area and investigated lichen specimens

A total of 94 lichen samples (69 saxicolous, 25 terricolous) were collected along the chronosequence of the Ödenwinkelkees glacier forefield (Hohe Tauern National Park, Austria; Electronic Supplement Fig. S1). Eleven 1×1 m plots from the Research Platform Ödenwinkel (Junker et al. 2020) were selected to represent distinct moraine ages and grouped into successional stages (Fig. 1; Appendix Tab. A1).

Lichen diversity was pre-assessed morphologically on site. In order not to disturb the species composition in the plots, only one sample/species was collected per plot (duplicates excluded post-hoc) by using sterile scalpels or forceps and stored in labelled tubes for molecular analyses. We were not able to collect herbarium vouchers for our molecular samples because the plots were part of a long term ecological observation study and the physical conditions were supposed to be left as unaltered as possible. We prioritized the advantage of the inventory for comparison of Research Platform Ödenwinkel over reproducibility. With reference to the plot and top view image, the studied lichen thalli can be assessed on site.

Top-view plot photographs were taken using a handheld DSLR camera (Sony Alpha 77; Electronic Supplement Fig. S1).

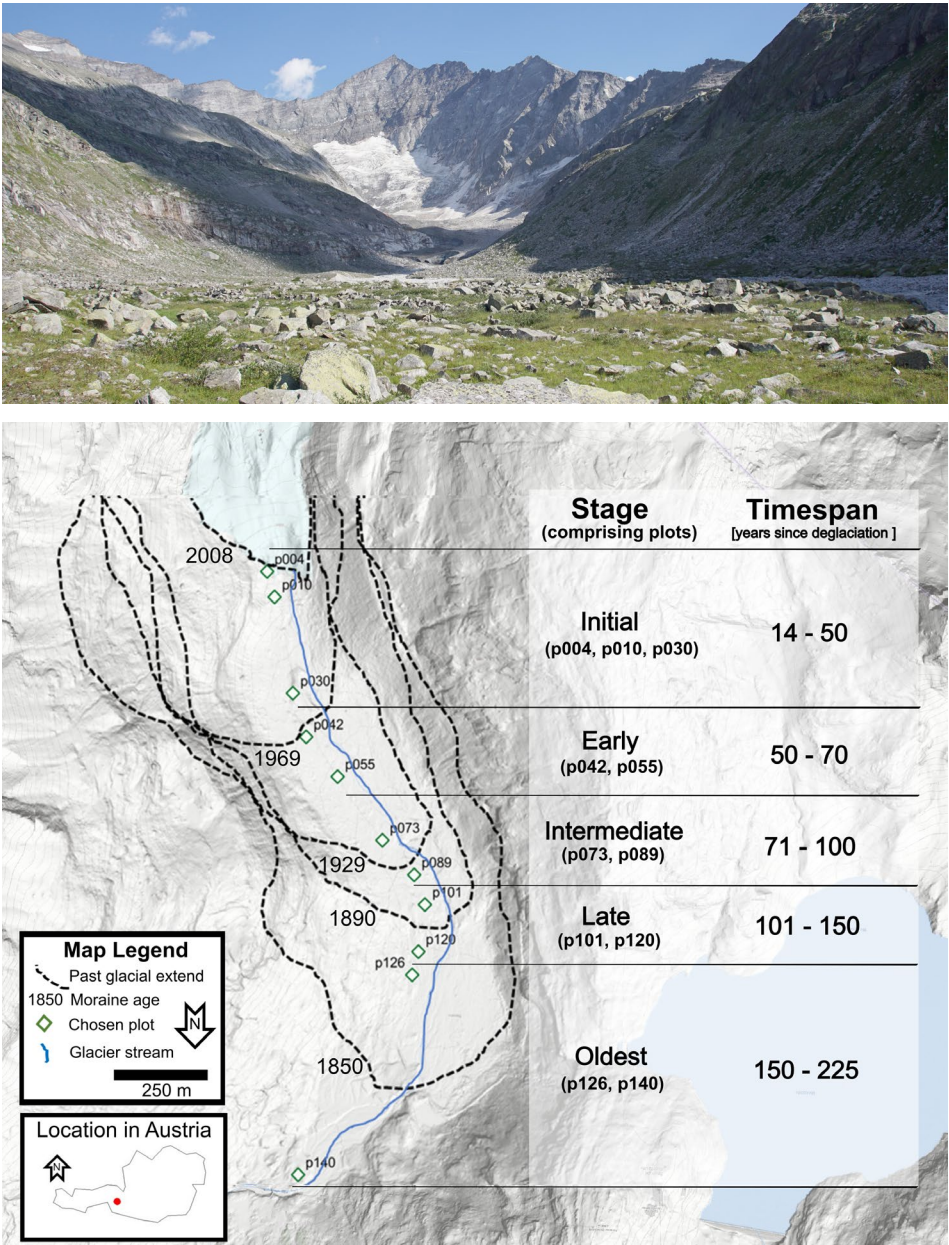


Fig. 1: Chosen plots of the Research Platform Ödenwinkel (Junker et al., 2020) with location in Austria, past glacier extent, and successional stages assigned in this study. The map was created using QGIS (v.3.16; and is based on basemap layers of Austrian administrations (www.basemap.at). | **Abb. 1:** Ausgewählte Parzellen der Forschungsplattform Ödenwinkel (Junker et al., 2020) in Österreich, ehemaligem Gletscherausräum und in dieser Studie verwendeten Sukzessionsstadien. Die Karte wurde mit QGIS (v.3.16; www.qgis.org) erstellt und basiert auf Basiskartenebenen österreichischer Behörden (www.basemap.at).

Molecular Analyses

Total genomic DNA was extracted from small thallus fragments using the DNeasy Plant Mini Kit (Qiagen), followed by further purification with the ZymoBIOMICS DNA Miniprep Kit (Zymo Research), following the manufacturers' protocols with minor modifications (Ruprecht et al. 2020). For amplification of the internal transcribed spacer (ITS) region of the nuclear ribosomal DNA, taxon-specific primer pairs were used:

Mycobiont. ITS1F and ITS4 (Gardes & Bruns 1993; White et al. 1990) were used with standard conditions (Ruprecht et al. 2020). Failed reactions were repeated using a semi-nested PCR with ITS1 and ITS4 (White et al. 1990).

Photobiont. To assess the presence of different green microalgae associated to the mycobiont, a broad screening along the ITS region was performed using the different primers pairs ITS4T and ITS1T (Kroken & Taylor 2000), ITS4 and nr-SSU-1780-5' (White et al. 1990; Piercey-Normore & DePriest 2001;) as well as ITS2-antisense A and ITS1-sense A (Ruprecht et al. 2014) as described in Ruprecht et al. (2020).

Unpurified PCR products were sent to Eurofins Genomics (Germany) for Sanger sequencing.

Species delimitation

Sequences were edited and aligned using the software Geneious (v.6.1.8.; <http://www.geneious.com>) MAFFT v7.017 (Katoh et al.2002).

Since we were not allowed to collect herbarium specimens in order to minimize disturbance to the habitat, we identified the samples using a BLAST search (www.blast.ncbi.nlm.nih.gov) for all accessions and included both blast search results and own sequences in comparative ML trees for the mycobionts. Since our own sequences were available, the samples from the family Lecideaceae were added to the existing phylogeny from Ruprecht et al. 2020 (SI 2) in order to assign them more accurately. For all the other sequences we downloaded matching sequences and combined them with the samples of the study in a Maximum Likelihood analysis using the IQ-TREE web server with default settings (Nguyen et al. 2015) to define the different species groups (SI 3). Tree visualization was performed with FigTree v1.4.4 (Rambaut 2018). The photobionts were solely assigned via BLAST search, the identity values were shown directly in Appendix Tab. A2.

Additionally, taxonomic assignments of mycobionts were based on alignment with field photos. Top-view plot photographs were taken using a handheld DSLR camera (Sony Alpha 77; Electronic Supplement Fig. S1).

Image-based coverage analysis

Top-view photographs of the plots were rectified in R (R Core Team 2022) using the packages devtools (Wickham et al. 2022), gplots (Warnes et al. 2016), and gdalUtilities (O'Brien 2019). Spatial analysis of surface coverage was conducted in QGIS v.3.16 using the coordinate reference system WGS84 / Pseudo-Mercator (EPSG:3857). Polygons were

manually delineated at multiple magnification levels to classify surface types. The area of each polygon was then calculated automatically by the software, allowing percentage cover of each surface class to be derived.

The following cover classes were distinguished:

- Vegetation (vascular plants and mosses)
- Rock (coarse substrate, $\varnothing > 63$ mm)
- Soil (fine substrate, $\varnothing < 63$ mm, without visible biological growth)
- Terricolous lichens
- Saxicolous lichens

In addition, the total surface area of *Rhizocarpon* spp. characterized by yellow-coloured thalli (hereafter referred to as yellow *Rhizocarpon*) was separately delineated and quantified.

Statistical analyses

To explore lichen community dynamics along the successional gradient, we conducted a series of univariate and multivariate analyses using R (R Core Team 2022).

Yellow rhizocarpons. The dataset was corrected for outliers in thallus size separately for early (<70 years) and late (>70 years) successional stages based on interquartile range criteria. Log-transformation was applied to normalize the data. Group differences were tested using analysis of variance (ANOVA) followed by a Tukey HSD post hoc test. Assumptions of homoscedasticity and normality were assessed by visual inspection of model residuals. Group-level means and standard deviations were calculated to visualize trends across the chronosequence. For correlation analyses, Spearman's rank correlation was used.

Multivariate analyses: For all multivariate analyses, the package *vegan* in R (Oksanen et al. 2013) was applied.

Non-metric multidimensional scaling (NMDS) was applied to a presence/absence species matrix (Euclidean distance, $k = 2$) and ordihulls were drawn depicting rock coverage (<30% vs. >30%) and species richness (<6 vs. >6).

Principal Component Analysis (PCA) was performed on raw coverage data (area in mm^2) combined with environmental variables from Junker et al. (2020), including soil temperature, pH, and concentrations of nitrogen (N), phosphorus (P), magnesium (Mg), and potassium (K), as well as substrate age. Variables were standardized prior to analysis.

Redundancy Analysis (RDA) was used to assess relationships between lichen species composition and environmental conditions. The species matrix was the same as in NMDS and

the environmental matrix included the raw coverage data used for the PCA. Significance was tested with 999 permutations.

Ecological assignment

To identify meaningful patterns in symbiotic associations and to reduce noise caused by single-species occurrences, both myco- and photobionts were grouped into ecologically and functionally coherent categories. The classification followed a stepwise decision scheme based on the ecological and morphological traits of the lichen-forming fungi (Tab. 1):

- **Substrate Affinity:** First, species were divided by substrate: terricolous vs. saxicolous. Substrate type is one of the most consistent ecological filters along glacier forefield chronosequences.
- **Genus-Level Identity:** Species were then grouped at the genus level when multiple representatives of a genus occurred in the dataset. This allowed grouping of functionally or ecologically similar species.
- **Family-Level Identity:** In cases where genus-level resolution was not sufficient (e.g. crustose lichens with reduced morphology), species were grouped at the family level, particularly within Lecideaceae, which includes morphologically difficult to assign taxa such as *Lecidea* and *Porpidia*.

Tab. 1: Ecological groupings of mycobiont taxa based on a stepwise classification scheme. | **Tab. 1:** Ökologische Gruppierungen von Mykobionten-Taxa auf der Grundlage eines schrittweisen Klassifizierungsschemas.

Group	Grouping scheme
stereocaulon_soil	1. Substrate: terricolous; 2. Genus: <i>Stereocaulon</i> sp.
stereocaulon_rock	1. Substrate: saxicolous; 2. Genus: <i>Stereocaulon</i> sp.
aspicilia	1. Substrate: saxicolous; 2. Genus: <i>Aspicilia</i> sp.
bellemerea	1. Substrate: saxicolous; 2. Genus: <i>Bellemerea</i> sp.
cetraria	1. Substrate: terricolous; 2. Genus: <i>Cetraria</i> sp.
lecanora	1. Substrate: saxicolous; 2. Genus: <i>Lecanora</i> sp.
rhizocarpon	1. Substrate: saxicolous; 2. Genus: <i>Rhizocarpon</i> sp.
umbilicaria	1. Substrate: saxicolous; 2. Genus: <i>Umbilicaria</i> sp.
lecideaceae	1. Substrate: saxicolous; 2. Genus: <i>Lecidea</i> sp. & <i>Porpidia</i> sp.; 3. Family: Lecideaceae
cladonia_r	1. Substrate: terricolous; 2. Genus: <i>Cladonia</i> sp.; 3. Family: Cladoniaceae; 4. "Reindeer lichens" with extensively branched morphology
cladonia_s	1. Substrate: terricolous; 2. Genus: <i>Cladonia</i> sp.; 3. Family: Cladoniaceae; 4. Shrubby morphology with podetia

- **Functional Morphology:** Finally, functional or growth-form traits were used to refine groupings, particularly for morphologically diverse genera like *Cladonia* P.Browne (e.g. differentiating extensively branched “reindeer lichens” from shrubby podetia-forming species).

Asterochloris and *Trebouxia* Photobionts were grouped accordingly. All other photobionts were grouped as OGEM (“Other Green Eukaryotic Microalgae”). This classification aimed to reflect ecological strategies relevant to succession, rather than strict phylogenetic relationships.

Results

Species delimitation

Species-level identification was successfully obtained for 84 mycobionts and 72 photobionts.

Mycobionts: Among the taxonomically challenging groups, five distinct clades were identified within Lecideaceae (*Lecidea promiscens* Nyl., *Lecidea* sp., *L. plana* (J. Lahm) Nyl, *Porpidia macrocarpa* (DC.) Hertel & A.J.Schwab, and *Lecidea* sp. UR01405). All other specimens were assigned to species level via BLAST search to the genera *Cladonia*, *Rhizocarpon* Ramond ex DC., *Stereocaulon* Hoffm., *Bellemerea* Hafellner & Cl.Roux, *Lecanora* Ach., *Umbilicaria* Hoffman, *Aspicilia* A.Massal., and *Cetraria* Ach.

Photobionts: 6 species were assigned to the genus *Asterochloris* including *A. glomerata* (Warén) Skaloud & Peksa, *A. irregularis* (Hildreth & Ahmadijan) Skaloud & Peksa, *A. lobophora* (Skaloud & Peksa 2015), *A. stereocaulonicola* Y.J.Kim, J.I.Kim & W.Shin and the OTUs *A. sp.* Vancourova A588, *A. sp.* 2709. The *Trebouxia* sequences formed two major clusters corresponding to OTUs *Trebouxia* (*Tr_I01*) and *T. (Tr_S02)* (Muggia et al. 2020)

Full species assignments are listed in Appendix Tab. A2, phylogenetic trees are provided in Electronic Supplement Figs S2–S3.

Species assessment and grouping

From 84 successfully sequenced mycobionts, 64 unique occurrences (one species per plot) were retained, comprising 42 saxicolous and 23 terricolous taxa. Species richness varied across plots and generally peaked (10 species) in mid-successional stages (Fig. 2), while the youngest and oldest plots exhibited lowest species richness (p004: 1 species; p010: 2 species; p140: 3 species).

Mycobionts. In total, 30 mycobiont species from 10 genera were identified and grouped into 11 ecologically coherent categories based on substrate affinity, morphology, and taxonomy (Fig. 3). The most widespread species were *Lecidea promiscens* and *Rhizocarpon geographicum* (L.) DC., each found on 8 plots. *Stereocaulon alpinum* Laurer and *Lecanora polytropa* (Hoffm.) Rabenh. were observed on 5 plots. *Bellemerea* sp. and *Rhizocarpon polycarpum* (Hepp ex Arnold) Th.Fr. were found on 4 plots. *Stereocaulon nanodes* Tuck occurred on 3 plots, one specimen growing on rock and the others on soil. One species only occurred

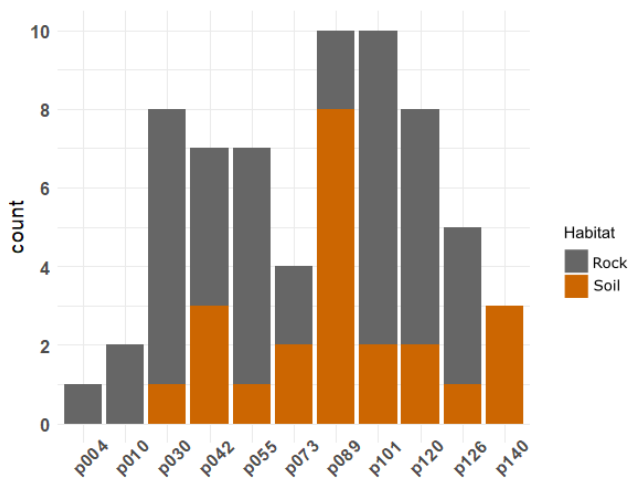


Fig. 2: Species richness and habitat distribution across plots. Bar plots showing the number of unique lichen species per plot highlighting shifts in richness and substrate preference along the successional gradient. | **Abb. 2:** Artenreichtum und Lebensraumverteilung über die Parzellen hinweg. Balkendiagramme zeigen die Anzahl der verschiedenen Flechtenarten pro Parzelle und verdeutlichen Veränderungen im Artenreichtum und in der Substratpräferenz entlang des Sukzessionsgradienten.

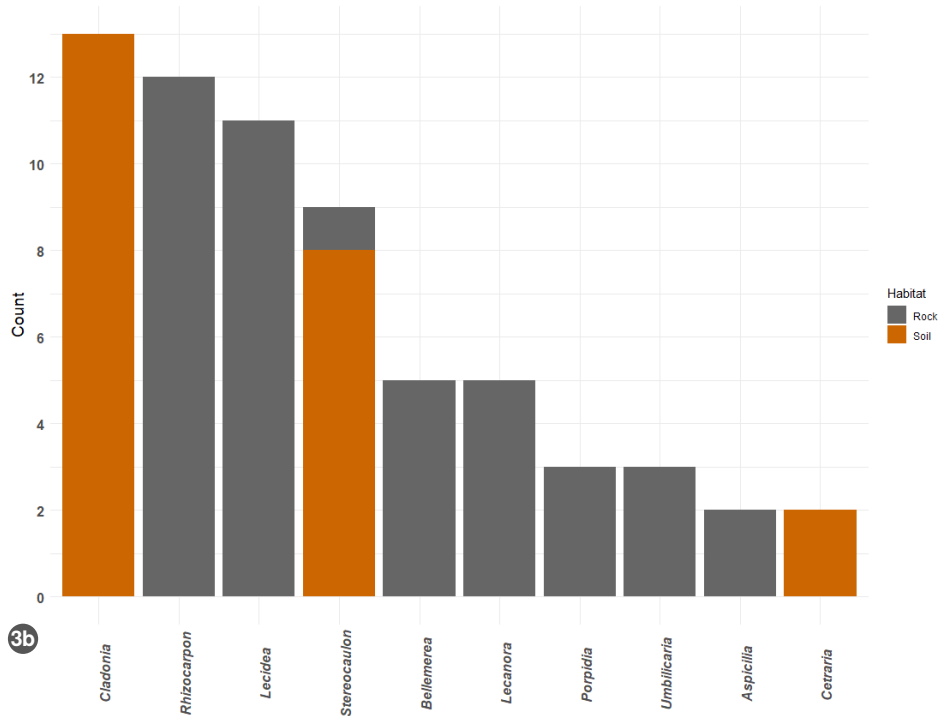
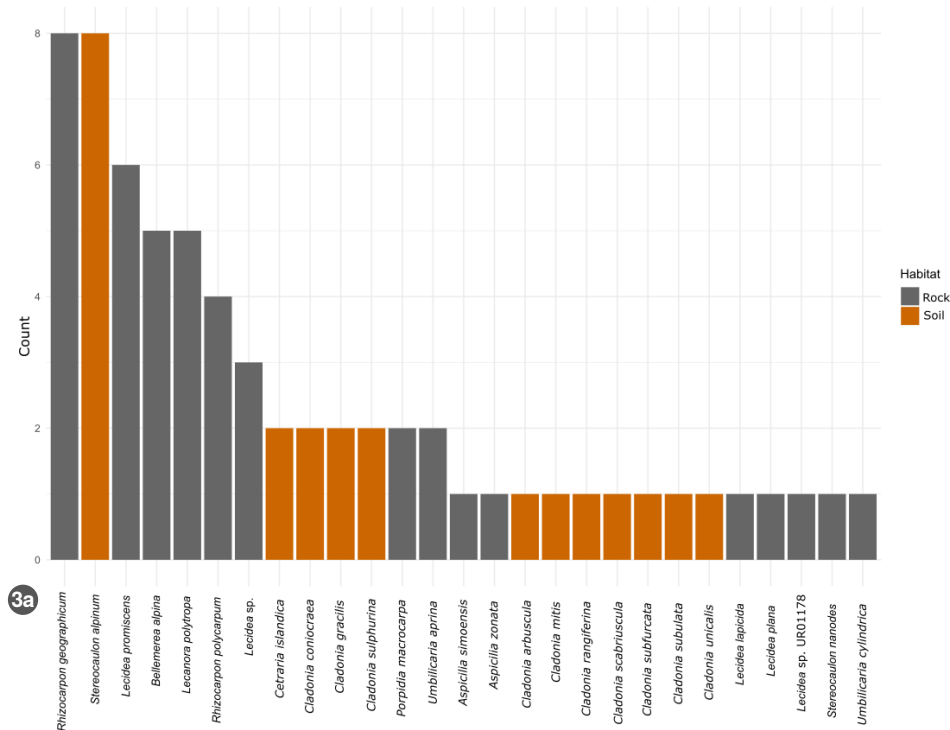
on a single plot, such as *Lecidea plana* (J. Lahm) Nyl.. The heterogeneous genus *Cladonia* P. Browne exhibited the highest number of different species ($n=11$).

Photobionts. 64 sequences revealed 11 distinct taxa: 6 species of the genera *Asterochloris*, two OTUs of *Trebouxia*, and one each of *Chloroidium* Nadson, *Pseudochlorella* J.W.G.Lund, 1955 and an ‘uncultured algal isolate’. The most common photobionts were *Tr_I01* and *Tr_S02*, primarily associated with saxicolous mycobionts, while *Asterochloris glomerata* and *A. irregularis* were more frequently linked to terricolous partners (Fig. 4).

Myco–photobiont network structure

Bipartite networks were calculated for all observed associations between mycobiont species and their respective photobiont taxa (Fig. 5). The overall network showed an intermediate specialization with an H_2' value of 0.53. While some mycobionts (e.g. *Aspicilia* spp., *Umbilicaria* spp.) were associated exclusively with a single photobiont, others – such as *Stereocaulon alpinum*, *Lecidea promiscens*, and *Rhizocarpon polycarpum* – were associated with multiple photobionts, including different genera.

Additionally, bipartite networks were calculated for five successional stages (Fig. 6). The highest H_2' value was observed in the late stage ($H_2' = 0.80$: highly specialized), followed by the initial stage ($H_2' = 0.59$). The young ($H_2' = 0.14$) and intermediate ($H_2' = 0.24$: highly generalized) stages showed lower specialization, while the oldest stage exhibited no network-level specialization ($H_2' = 0.00$). Shifts in photobiont associations were observed for different mycobionts, including *Lecidea promiscens* and *Rhizocarpon polycarpum*,



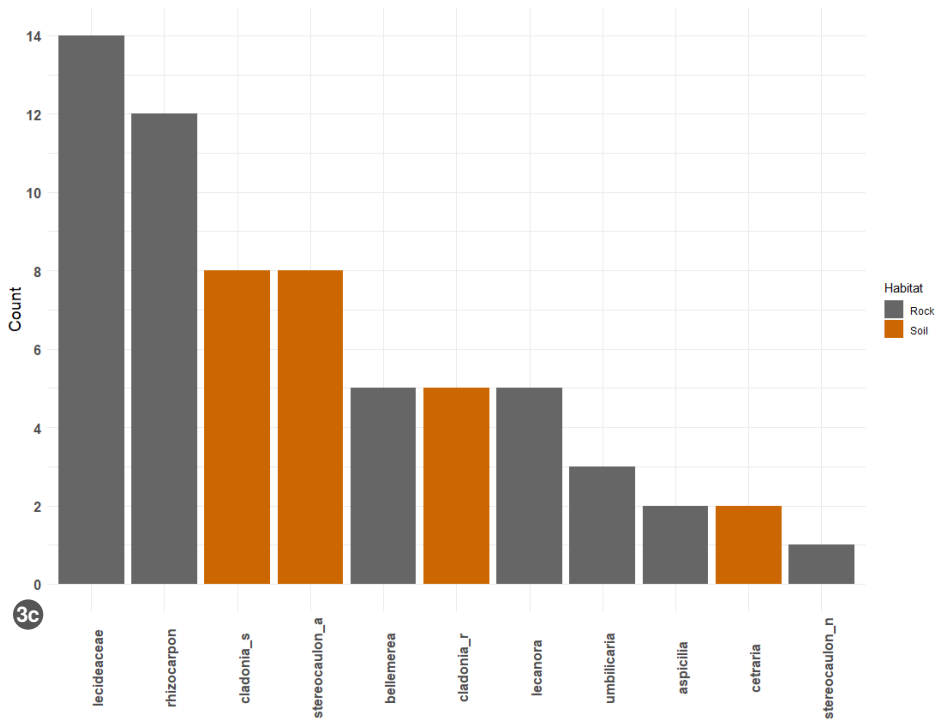


Fig. 3: Bar plots showing species richness of lichen taxa identified in this study. (a) species-level occurrences across plots, (b) distribution across genera, (c) grouping ecological categories. | **Abb. 3:** Balkendiagramme zur Artenvielfalt der in dieser Studie identifizierten Flechten-Taxa. (a) Vorkommen auf Artenebene in den verschiedenen Parzellen, (b) Verteilung über die Gattungen, (c) Einteilung in ökologische Kategorien.

indicating variable symbiotic patterns across successional stages. The two *Trebouxia* OTUs observed in this study were the most frequently associated photobionts and occurred across all stages. While the *Trebouxia* OTUs were dominant in the initial, young, and late stages, *Asterochloris* taxa prevailed in the intermediate stage: Despite *A. glomerata* occurring in almost all stages, they showed most associations to terricolous mycobionts in the intermediate stage. *A. irregularis* and *A. stereocaulonicola* occurred exclusively in this stage and exhibited an association to four different mycobiont taxa (including saxicolous *Porpidia macrocarpa*).

Across the successional gradient, *Stereocaulon alpinum* was the only mycobiont species observed in all five stages and associated with up to three different photobiont taxa. In contrast *S. nanodes* occurred only in the initial and late stage. Notably, OGEN-photobionts were only observed in two stages: *Chloroidium saccharophilum* (W.Krüger) Darienko et al. in the initial stage, and *Pseudochlorella pyrenoidosa* as well as an ‘unknown algal isolate’ in the late stage.

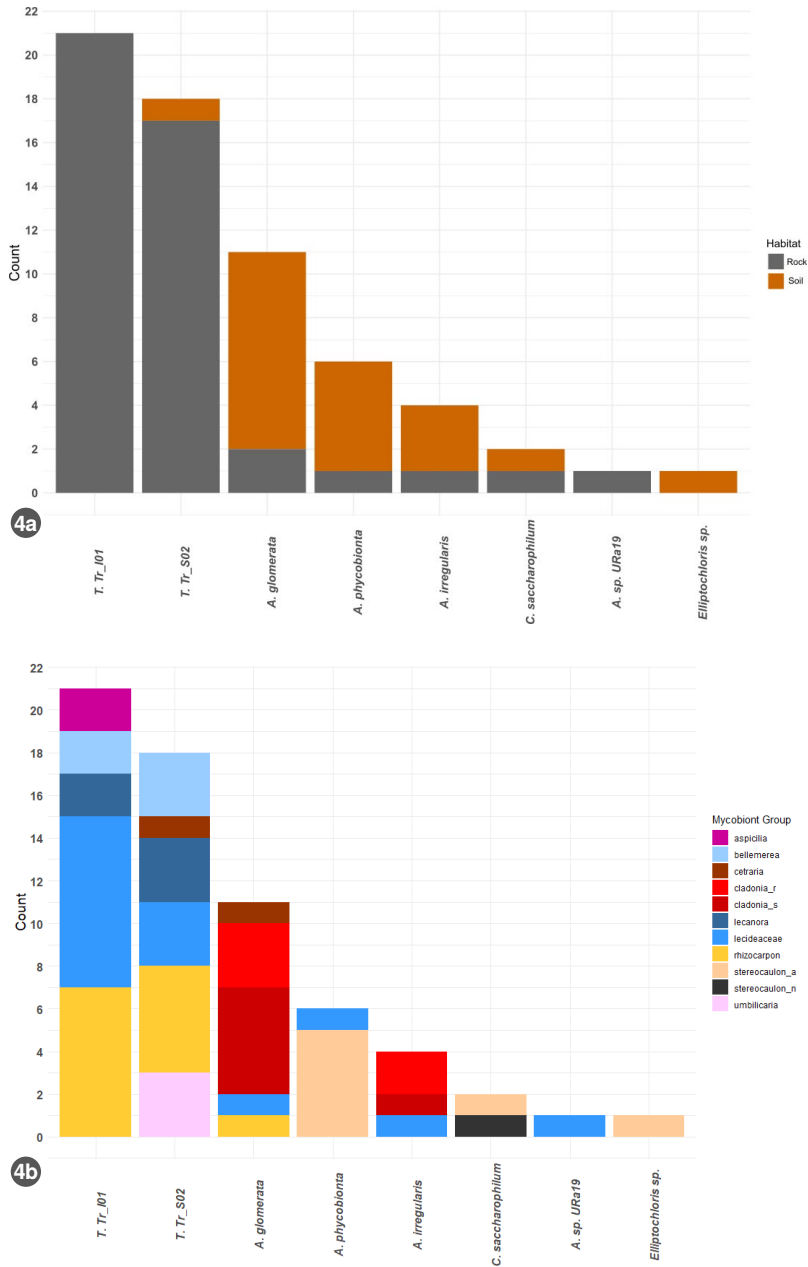


Fig. 4: Bar plots showing the occurrence of photobiont taxa ($n = 64$) across all lichen samples. (a) Distribution by substrate of the associated mycobiont (saxicolous vs. terricolous). (b) Associations of photobionts with ecologically defined mycobiont groups. | **Abb. 4:** Balkendiagramme, die das Vorkommen von Photobionten-Taxa ($n = 64$) in allen Flechtenproben zeigen. (a) Verteilung nach Substrat der assoziierten Mykobionten (saxikol vs. terrikol). (b) Assoziationen von Photobionten mit ökologisch definierten Mykobionten-Gruppen.

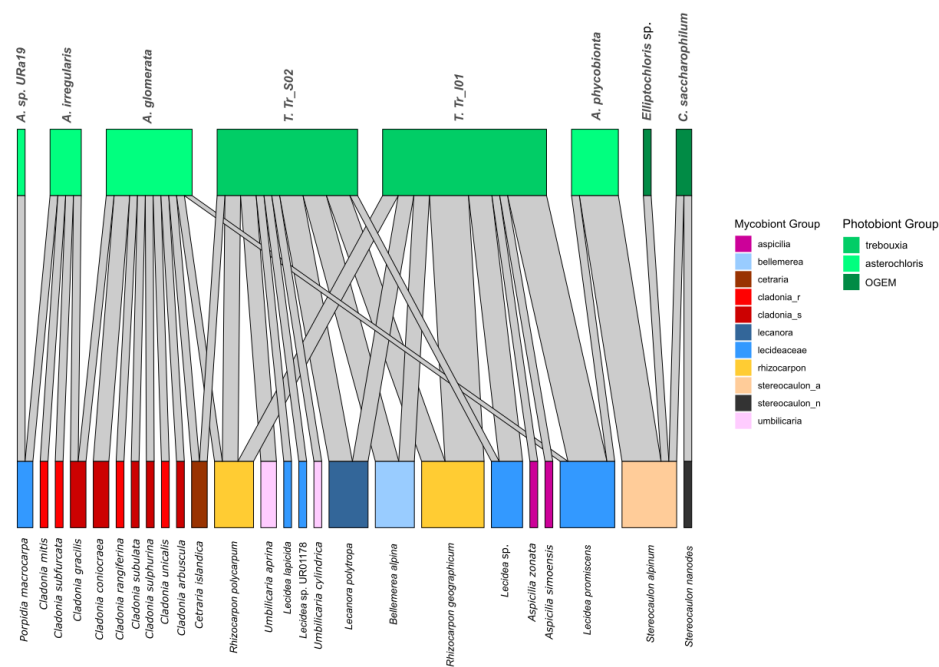
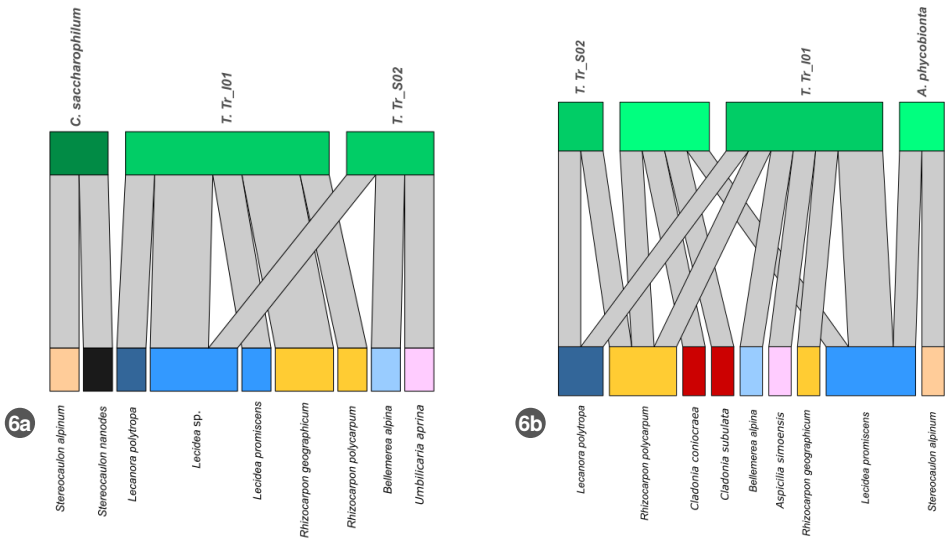


Fig. 5: Bipartite network of all observed mycobiont–photobiont associations ($H_2' = 0.52$). Mycobionts (lower level) and photobionts (upper level) are coloured by ecological group. Edge width indicates interaction frequency. | **Abb. 5:** Bipartites Netzwerk aller beobachteten Mykobionten-Photobionten-Assoziationen ($H_2' = 0,52$). Mykobionten (untere Ebene) und Photobionten (obere Ebene) sind nach ökologischen Gruppen farblich gekennzeichnet. Die Breite der Verbindungsbalken gibt die Häufigkeit der Interaktionen an.



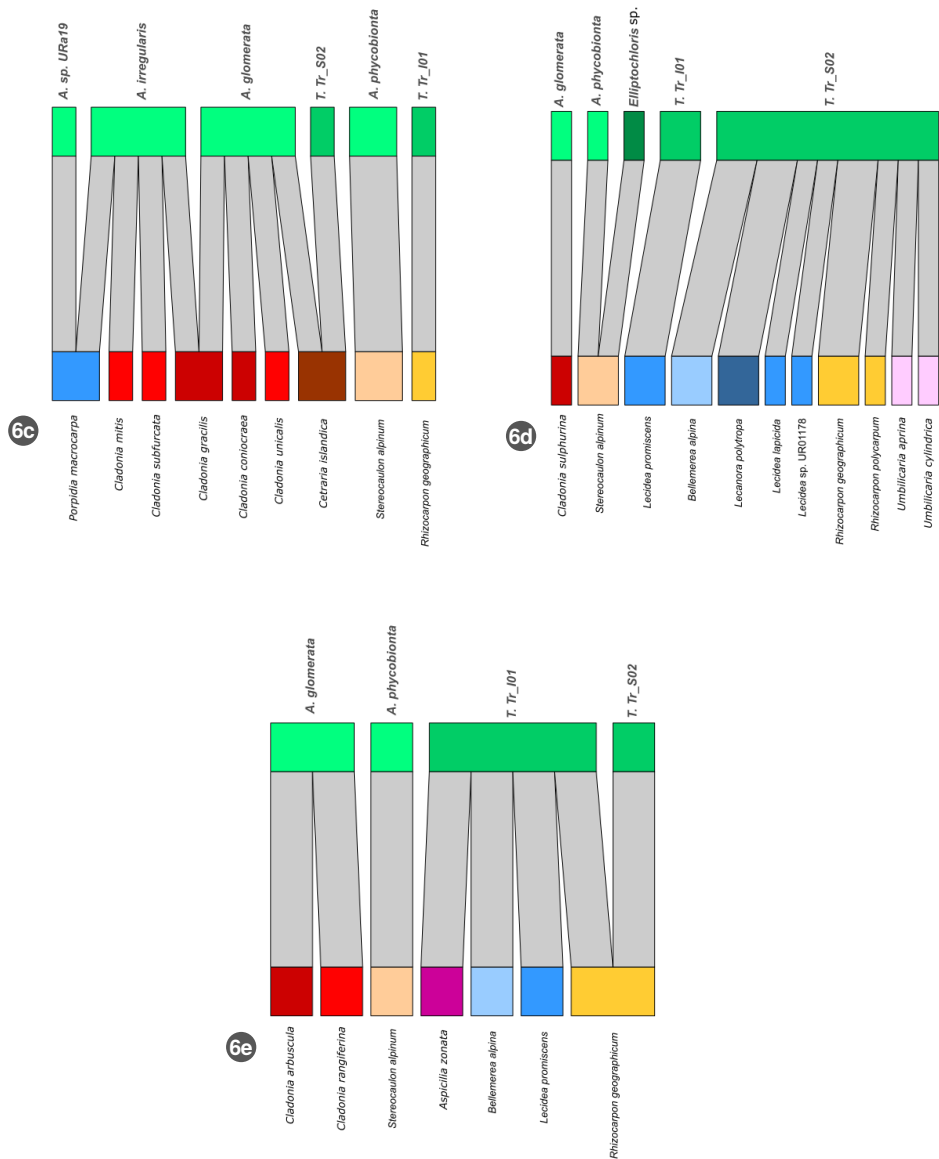


Fig. 6: Stage-specific bipartite networks of mycobiont–photobiont associations across five successional stages. (a) Initial (p004, p010), (b) Young (p042, p055), (c) Intermediate (p073, p089), (d) Late (p101, p120), (e) Oldest (p126, p140). Colours denote ecological groupings (colour code according to Fig. 5). Edge width indicates interaction frequency. | **Abb. 6:** Stadiumspezifische bipartite Netzwerke von Mykobiont-Photobiont-Assoziationen über fünf Sukzessionsstadien hinweg. (a) Anfangsstadium (p004, p010), (b) Jungstadium (p042, p055), (c) Zwischenstadium (p073, p089), (d) Spätes (p101, p120), (e) Ältestes (p126, p140). Farben kennzeichnen ökologische Gruppierungen (Farbcode gemäß Abb. 5). Die Breite der Verbindungsbalken gibt die Häufigkeit der Interaktionen an.

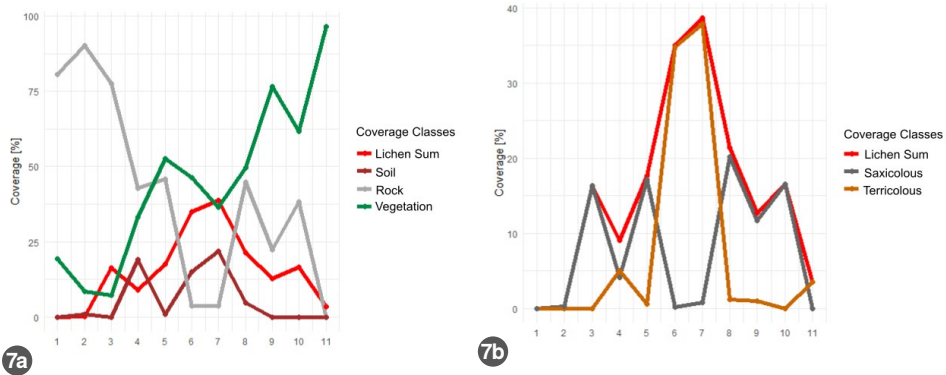


Fig. 7: Coverage trends of different substrate and lichen classes along the successional gradient. (a) Vegetation, soil, rock and total lichen cover; (b) Total lichen cover separated into terricolous and saxicolous growth forms. | **Abb. 7:** Bedeckungstrends verschiedener Substrat- und Flechtenklassen entlang des Sukzessionsgradienten. (a) Vegetations-, Boden-, Gesteins- und Gesamtflechtenbedeckung; (b) Gesamtflechtenbedeckung unterteilt in terrikole und saxikole Wuchsformen.

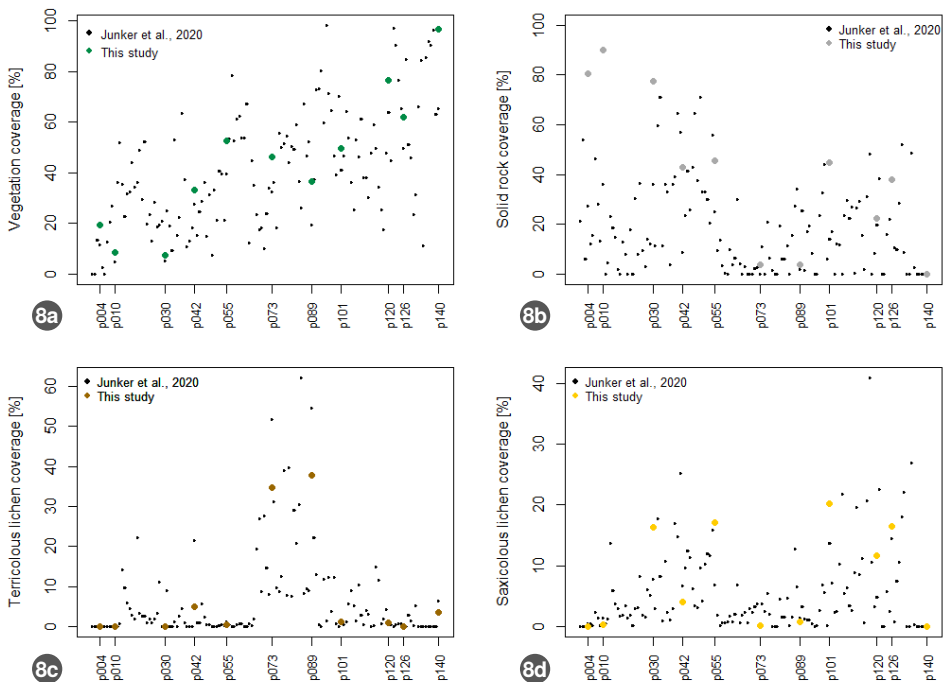


Fig. 8: Comparison of photo-based coverage data from this study (coloured dots) with field-based data of all 140 plots from Junker et al. (2020) (black dots) across all plots. (a) Vegetation, (b) solid rock, (c) terricolous lichens, (d) saxicolous lichens. | **Abb. 8:** Vergleich der fotobasierten Abdeckungsdaten aus dieser Studie (farbige Punkte) mit den Felddaten aller 140 Parzellen aus Junker et al. (2020) (schwarze Punkte) über alle Parzellen hinweg. (a) Vegetation, (b) festes Gestein, (c) terrikole Flechten, (d) saxikole Flechten.

Coverage patterns along succession

Coverage estimates from photo-assessment reveal clear trends along the successional gradient (Fig. 7; Electronic *Supplement Fig. S1*). Vegetation cover increased to >95% with plot age ($R^2 = 0.70$), while rock cover declined from ~80% on the youngest plots to 0% on the oldest (Fig. 7a). Lichen cover peaked on intermediately aged plots (~39%) and was minimal at both early and late successional stages (Fig. 7b). This mid-successional peak was largely driven by terricolous lichens, particularly *Stereocaulon alpinum* (Electronic *Supplement Fig. S1*).

A comparison with field-assessed data by Junker et al. (2020) (Fig. 8a-d) confirms the general trends. Vegetation and lichen patterns broadly agree between studies, however, vegetation increase was steeper in our data and Junker et al. 2020 assessed terricolous lichen coverage of intermediate plots up to >60%. Rock cover estimates diverged slightly, with Junker et al. 2020 reporting lower values in the youngest stages, though both datasets showed a sharp decline towards intermediate plots.

Yellow *Rhizocarpon* thallus area

The coverage data revealed a significant linear increase in mean thallus area of yellow *Rhizocarpon* specimens with age of deglaciation (LM: Df = 5, $F = 54.08$, $p < 0.01$; Fig. 9a). The differences in thallus size between plots were statistically confirmed via ANOVA followed by a Tukey-HSD post-hoc test (Fig. 9b). The latest successional plot with yellow *Rhizocarpon* presence (p126) exhibited significantly larger thalli than all others.

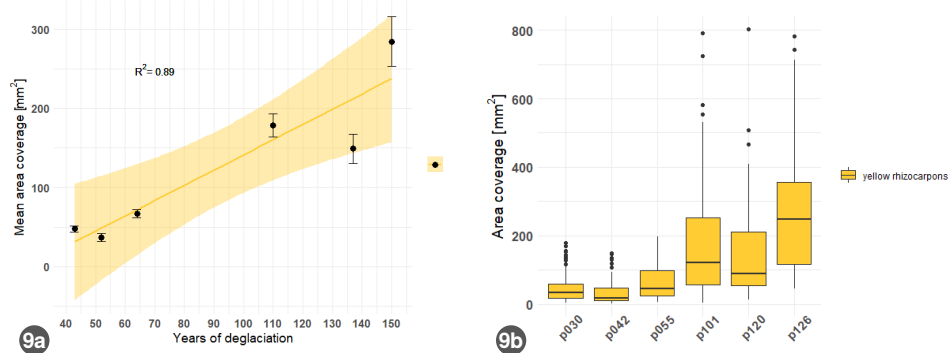


Fig. 9: (a) Linear regressions showing strong positive correlation ($R^2 = 0.89$) between mean yellow *Rhizocarpon* thallus size and plot age (obtained from Junker et al. 2020); (b) Thallus areas of yellow *Rhizocarpon* individuals across plots ordered by age. Lowercase letters indicate statistical groupings (Tukey HSD, $p < 0.05$). | **Abb. 9:** (a) Lineare Regressionen, die eine starke positive Korrelation ($R^2 = 0.89$) zwischen der durchschnittlichen Größe des Thallus von gelbem *Rhizocarpon* und dem Alter der Parzelle zeigen (entnommen aus Junker et al. 2020); (b) Thallusflächen von gelbem *Rhizocarpon*-Individuen über Parzellen hinweg, geordnet nach Alter. Kleinbuchstaben kennzeichnen statistische Gruppierungen (Tukey HSD, $p < 0.05$).

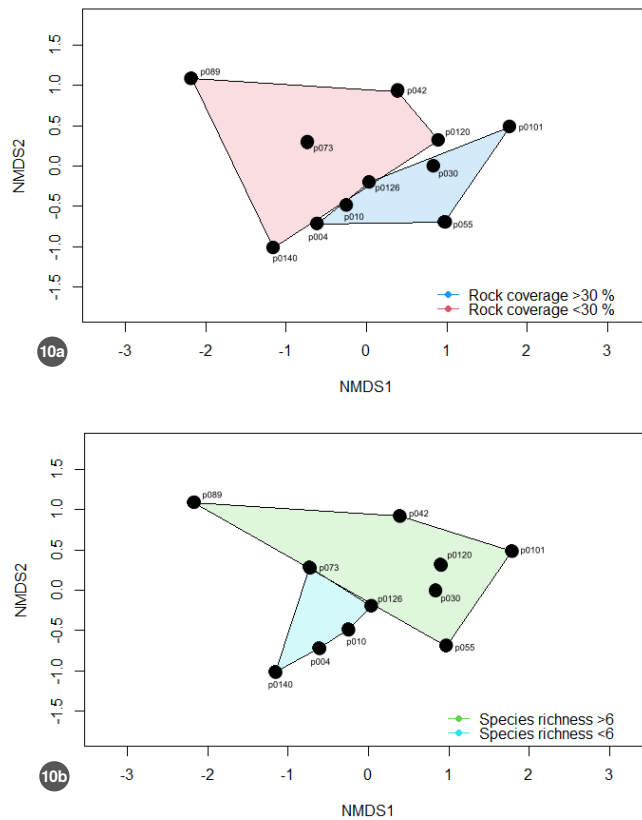
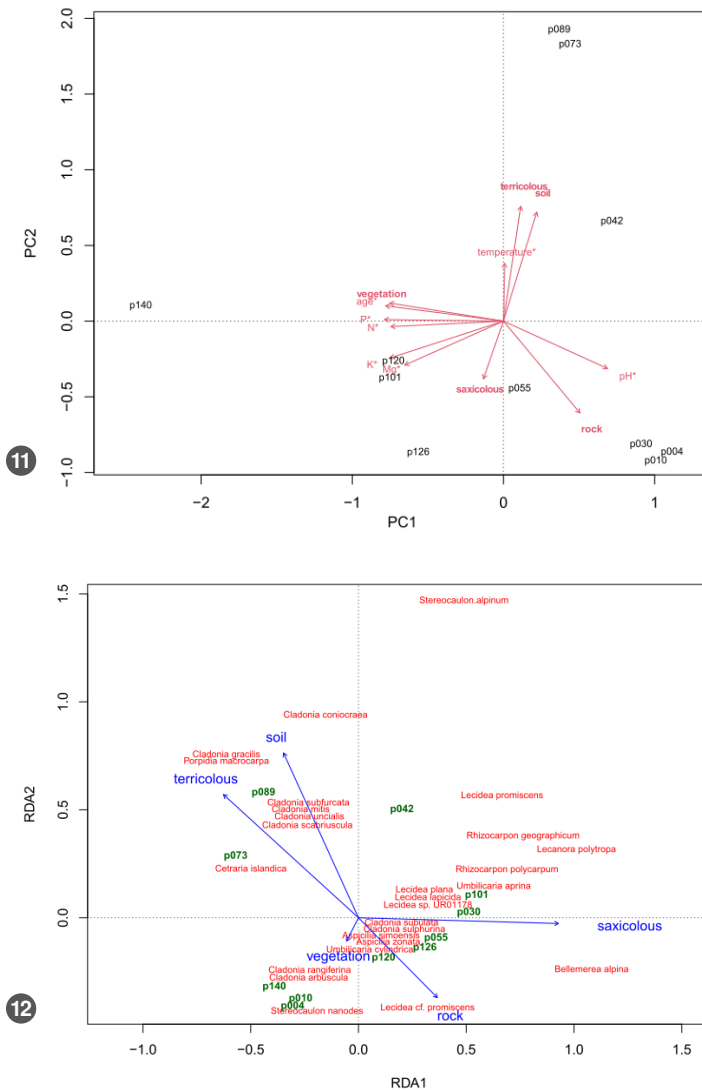


Fig. 10: NMDS ordination with plots grouped by (a) rock coverage (>30% vs. <30%) and (b) species richness (>6 vs. <6 species). | **Abb. 10:** NMDS-Ordination mit Parzellen gruppiert nach (a) Gesteinsbedeckung (>30 % vs. <30 %) und (b) Artenreichtum (>6 vs. <6 Arten).

Multivariate analyses

Community structure was summarized using a two-dimensional NMDS (stress = 0.12). The NMDS1 axis tends to reflect rock coverage with a trend of terricolous-dominated communities (low rock cover) clustering at lower scores and saxicolous-dominated communities (high rock cover) at higher scores (Fig. 10a). NMDS2 tends to reflect a gradient in species richness, with species-poor plots (youngest and oldest) clustering at lower NMDS2 values and species-rich plots (intermediate ages) higher up (Fig. 10b). This separation by species richness was statistically supported (PERMANOVA: $F = 2.47$, $p = 0.015$).

In a PCA that included physico-chemical data of Junker et al. (2020) the first two axes (76% variance) confirmed two key correlations: (1) vegetation cover, nutrients (N, P, K, Mg) and moraine age increase together and are negatively related to pH and rock cover; (2) soil and terricolous-lichen cover track mean annual temperature and are negatively related to saxicolous cover (Fig. 11). The PCA suggests main environmental characterizations



of the plots: rock coverage and pH (p004, p010, p030), saxicolous lichen coverage (p055, p126), terricolous/ soil coverage and temperature (p089, p073), vegetation and nutrients (p101, p120, p140). One plot (p042) is found in the space between the axis of pH and soil coverage.

An RDA ordination plot links community composition with coverage data as constraining variables (Fig. 12). These variables explained 74.72% of the variance (global permutation test, $F = 1.79$, $p = 0.007$). The first axis reflects the terricolous–saxicolous trade-off, while the second axis separates species-rich intermediate plots from species-poor plots in the early and late stages. Plotting highest on RDA2 and intermediate at RDA1, *Stereocaulon alpinum* reflects high species richness and transition between rock and soil dominated areas. Characteristic taxa fall into the expected quadrants: Saxicolous mycobionts like *Lecidea* spp. and *Bellemerea* sp. align with rock/saxicolous coverage and terricolous species like *Cladonia* spp. or *Cetraria islandica* (L.) Ach. align with soil/terricolous coverage. The communities of the assessed plots show distinct clusters along the constraining axes: Youngest and oldest plots (p004, p010, p126) cluster below the vegetation axis. The plots p030, p055, p101, p120, p126 show a tendency of plotting around the rock- and saxicolous axis, while p073 and p089 form a cluster around the soil- and terricolous axis. Plot p042 is characterized by positive scores on both RDA axes and is associated with both saxicolous and soil explanatory variables.

Discussion

Species richness and community clusters

By combining molecular identification and community analyses, this pilot study uncovers new insights into successional trends and symbiotic turnover in lichen communities of the Ödenwinkelkees glacier forefield.

Saxicolous lichens outnumbered terricolous lichens nearly twofold, mirroring patterns reported in other glacier forefields (Türk & Erschbamer 2010; Favero-Longo et al. 2012). The number of terricolous species falls at the lower end of the range as reported in other glacier forefields by Nascimbene et al. (2017) (15 species at Morteratsch forefield, CH; 41 Gaisbergferner forefield, AT) or Wietrzyk-Pelka et al. (2018) (24 at Ferdinandbreen forefield, NO; 82 at Rieperbreen forefield, NO). In agreement with these studies, low species richness was observed on the youngest moraines. Colonization typically requires 30–40 years of deglaciation, as earlier substrates remain too unstable (Türk & Erschbamer 2010; Nascimbene et al. 2017). While other studies (Favero-Longo et al. 2012; Nascimbene et al. 2017; Wietrzyk-Pelka et al. 2018) reported positive succession–diversity relationships along the gradient, the present data suggests a hump-shaped pattern, with peak richness and coverage occurring in intermediately aged plots (~80–100 years; Fig. 1 & 2). Yet, a drop in species richness was observed after 83 years of deglaciation (p073; Fig. 2) that was linked to the domination of *Stereocaulon alpinum* (see Electronic Supplement Fig. S1). Diversity was low on younger plots due to substrate instability, and in older plots because of vascular plant competition (Asplund et al. 2022). This non-monotonic trend emphasizes the influence of gradient length: studies limited to shorter successional spans would likely overlook the late-stage declines captured within the 225-year gradient of this study.

Lichen cover and species composition form distinct zones along the successional gradient, reflecting a structured pattern of ecological replacement. A pronounced “*terricolous belt*” is observed in the intermediate stage, characterized by high coverage (~39%) of terricolous lichens – primarily *Stereocaulon. alpinum* and *Cladonia* spp. – and low saxicolous presence (Fig. 7b), what is in accordance with Nascimbene et al. (2017), who reported similar areas of terricolous lichen dominance for comparable moraine ages across several European glacier forefields. Flanking this central terricolous zone are two “saxicolous belts”: a younger (~40–80 years) and an older (~100–160 years) stage, each dominated by saxicolous taxa such as *Lecidea promiscens*, *Lecanora polytropa*, and *Bellemerea* sp.. At both ends of the gradient (initial and oldest plots), lichen occurrence drops sharply, resulting in species-poor “edge communities” (Fig. 2 & 7).

These patterns are supported by multivariate ordinations. NMDS1 reflects a clear axis of substrate association, separating saxicolous and terricolous communities, while NMDS2 captures species richness gradients, with high values in intermediate stages and low values at the edges (Fig. 10). RDA similarly confirms community clustering along substrate and lichen cover gradients (Fig. 12). Plots within the saxicolous belts align with rock and saxicolous lichen coverage, whereas intermediate plots associate with soil and terricolous lichen cover. Edge plots show low diversity and align with high vegetation cover, which increases with successional age and acts as a proxy for community displacement (Nascimbene et al. 2017).

While most plots cluster distinctly, transitional stages are also present. Plot p042, though located within the younger saxicolous belt, exhibits high soil cover and substantial terricolous lichen presence – suggesting a lag in community turnover or transitional dynamics. Extensive investigations of several taxa in the same glacier forefield revealed a transition zone after ~60 years of deglaciation, where species turnover switches from stochastic occurrences towards deterministic processes such as niche filtering and biotic interactions (Hanusch et al. 2022). Aging ~55 years since deglaciation, p042 might reflect this transitional trend in community turnover.

Symbiont interactions and assembly dynamics

The mycobiont–photobiont associations observed in this study are consistent with previously reported symbiotic partnerships, such as *Cladonia*–*Asterochloris* (Steinová et al. 2019), *Lecidea*–*Trebouxia* (Ruprecht et al. 2020), and *Porpidia*–*Asterochloris* (Ruprecht et al. 2016). Our network analysis reveals that the terricolous belt coincides with a photobiont guild dominated by *Asterochloris* species. This photobiont genus with 6 different species (Appendix Tab. A2) appears to act as an ecological filter, structuring which mycobionts can establish. For example, *Porpidia. macrocarpa* was the only lecideoid mycobiont present exclusively in these intermediate plots and was associated with a distinct *Asterochloris* lineage. The strong presence of *Asterochloris* in intermediate plots may relate to microclimatic conditions, particularly temperature (Peksa & Škaloud 2011), as the abundance of terricolous lichens correlated with mean annual temperature in the PCA (Fig. 11). *Asterochloris* photobionts may be more thermophilic compared to the more stress-tolerant *Trebouxia*, which is able to thrive under colder or nutrient-poor extremes, such as in polar studies (e.g. Wagner et al. 2020).

Next to microclimate regimes, the exceptionally high lichen coverage- and diversity on intermediate plots may further be facilitated by fine-grained, nutrient poor soils, which support terricolous lichens while limiting vascular plant encroachment. The dominating species, *Stereocaulon alpinum* is a tripartite lichen, possessing cyanobacterial photobionts next to green algae and it was hypothesized, that additional cyanobacteria symbionts enhance colonizing capability by binding N from the surrounding air what is advantageous on nutrient-poor substrates (Rikkinen 2015).

Older plots in contrast show distinctly higher nutrient levels, fostering vascular plant growth and likely increasing competitive pressure on lichens (Junker et al. 2020; Asplund et al. 2022). This combination of favourable substrate conditions and reduced competition appears to define a temporal ecological niche that supports lichen dominance during intermediate succession. The lichen flora may, in turn, modify microclimatic and soil conditions, facilitating a transition toward vascular plant dominance (Longton 1988).

Interestingly, the initial and late successional stages exhibit elevated network specialization, potentially due to environmental filtering effects. Both stages are clearly dominated by *Trebouxia* photobiont-guilds. In the initial stage, *Tr_I01* is clearly the most dominant photobiont, which seems to be best adapted to low mean annual temperatures posed by the proximity to the glacier tongue. The late stage is dominated by *Tr_S02*, which is potentially adapted to higher temperatures.

Additionally, these two (initial and late) stages are marked by *Stereocaulon* species associating with OGEM-photobionts. This is in line with Vancurova et al. (2018), who report a wide ecological range of *Stereocaulon* species and the ability to associate with different photobionts of the genera *Asterochloris*, *Chloroidium* or *Vulcanochloris* Vancurová, Peksa, Nemcová & Skaloud. In the initial stage, *Stereocaulon nanodes* was exclusively associated to *Chloroidium saccharophilum*, while *S. alpinum* was associated to *Asterochloris* species throughout all other stages. This points towards *C. saccharophilum* might posing an advantage to *Stereocaulon* species for early colonization of ecologically challenging habitats, low temperatures, mobile substrate and limited nutrients (Barták et al. 2007; Türk & Erschbamer 2010; Wietrzyk-Pelka et al. 2018), likely being the most crucial environmental filters. In the late stage, *S. nanodes* associated to another OGEM algae, what possibly reflects a stress response due to vascular plant competition. The association of *Stereocaulon* species to microalgae like *C. saccharophilum* are rare (e.g. Beck 2002, Persoh et al. 2004, Ruprecht et al. 2014) and future studies should investigate the role of these exceptional symbiotic relations regarding assembly patterns and stress response (Vancurova et al. 2018).

Field-assessable groupings and successional signals

Field-accessible groups based on morphological traits proved effective in capturing successional dynamics, supporting the value of trait-based lichen ecology (Ellis et al. 2021). *S. alpinum* served as a key indicator of intermediate-aged plots within the terricolous belt, while *Rhizocarpon* spp. dominated older saxicolous belts and showed strong correlations between thallus area and terrain age. *Cladonia* species were most diverse in the terricolous belt, with 'cladonia_s' showing a narrower distribution than the more widespread 'cladonia_r'. In contrast, species of *Aspicilia* and *Umbilicaria* were mostly restricted to early or late

successional stages. Core saxicolous groups such as ‘lecanora’, ‘bellemerea’, and ‘lecideaceae’ dominated mature rock-dominated communities. *Porpidia macrocarpa*, although grouped within ‘lecideaceae’, was restricted to mainly terricolous plots and may warrant a separate group. Yet, these groupings – based on field-visible characters – may offer a practical framework for interpreting successional patterns (Nascimbene et al. 2017), even in the absence of molecular data or advanced taxonomic tools.

***Rhizocarpon* mean thallus area as proxy for succession?**

Lichenometric approaches commonly estimate moraine age based on the diameter of the largest thalli of yellow *Rhizocarpon* species (e.g. Mottershead & White 1972; Proctor 1983; Garibotti & Villalba 2009). Statistical approaches (e.g. Loso et al. 2014) have also been developed that rely primarily on thalli from the upper part of the size distribution. However, exceptionally large individuals may represent coalesced thalli or may have been gravitationally transported from upslope areas, which can introduce uncertainty into size-based age estimates (Osborn et al. 2015). Rather, than focusing on the largest thalli, this pilot assessment explored whether outlier-corrected mean thallus area of yellow *Rhizocarpon* specimens may also reflect successional development. Significant relationships were found with both deglaciation age and total saxicolous lichen cover. Although these results suggest that population-level metrics may capture successional trends, a direct comparison with traditional diameter-based lichenometric approaches would be required to evaluate whether mean thallus area provides a methodological advantage. Such comparisons may represent a promising direction for future studies.

Conclusion

This study presents one of the few molecular investigations of myco-/photobiont associations along a gradient in a glacier forefield (Beck et al. 2019), revealing distinct lichen communities well represented by field-assessable groups. Several of these groups serve as indicators of successional stage (Nascimbene et al. 2017) and environmental conditions. Photobiont-mediated guilds appear to structure mycobiont diversity along the successional gradient, and some associations – particularly the photobiont associations of *Stereocaulon* sp. (Vancurova et al. 2018) – are relevant and merit further study.

Standardized plots of Junker et al. (2020) enabled integration with abiotic and biotic datasets. Top-view imagery proved valuable for coverage assessment and for exploring an alternative age-dating method via outlier-corrected mean thallus area of yellow *Rhizocarpon*. This approach shows promise for broader application with expanded sampling and automated image analysis.

Overall, this pilot study advances understanding of lichen symbiont assembly in glacier forefields and highlights promising directions in molecular, and image-assisted research.

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Electronic supplement

S1: Rectified top-view images of the plots chosen for this study (marked according to plot number). | **S1:** Rektifizierte Bilder aus der Vogelperspektive der für diese Studie ausgewählten Parzellen (gekennzeichnet nach Parzellennummer).

https://www.zobodat.at/pdf/supp/Gindorf_Ruprecht_Supplement_1.png

S2: Phylogeny of *Lecidea* and *Porpidia* based on ITS sequences (Ruprecht et al. 2020) and accessions of this study. Bootstrap values indicate branch support (≥ 90 = high). Coloured boxes highlight species clusters including accessions from this study. | **S2:** Phylogenie von *Lecidea* und *Porpidia* basierend auf ITS-Sequenzen (Ruprecht et al. 2020) und Proben aus dieser Studie. Die Bootstrap-Werte geben die Verzweigungsstärke an (≥ 90 = hoch). Die farbigen Kästchen heben Artencluster hervor, welche Proben aus der vorliegenden Studie enthalten.

https://www.zobodat.at/pdf/supp/Gindorf_Ruprecht_Supplement_2.png

S3: This phylogenetic overview shows the best sequence matches of the samples from this study obtained from BLAST search across a wide range of genera. Species that could not be directly assigned were classified only at the genus level. | **S3:** Dieser phylogenetische Überblick zeigt die besten Übereinstimmungen der Proben aus dieser Studie, die durch eine BLAST-Suche über ein breites Spektrum von Gattungen ermittelt wurden. Arten, die nicht direkt zugeordnet werden konnten, wurden lediglich auf Gattungsebene klassifiziert.

https://www.zobodat.at/pdf/supp/Gindorf_Ruprecht_Supplement_3.png

S4: Phylogeny of *Trebouxia* based on ITS sequences from Ruprecht et al. (2020) and this study. Bootstrap values (0–100) indicate branch support (≥ 90 = high). Coloured boxes highlight species clusters including accessions from this study. | **S4:** Phylogenie von *Trebouxia* basierend auf ITS-Sequenzen (Ruprecht et al. 2020) und Proben aus dieser Studie. Die Bootstrap-Werte geben die Verzweigungsstärke an (≥ 90 = hoch). Die farbigen Kästchen heben Artencluster hervor, welche Proben aus der vorliegenden Studie enthalten.

https://www.zobodat.at/pdf/supp/Gindorf_Ruprecht_Supplement_4.png

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Appendix

Tab. A1: Year of deglaciation, elevation and coordinates for the eleven plots of Research Platform Ödenwinkel (Junker et al. 2020) chosen for this study. | **Tab. A1:** Jahr der Entgletscherung, Höhe und Koordinaten der elf für diese Studie ausgewählten Parzellen der Forschungsplattform Ödenwinkel (Junker et al. 2020).

Plot Number	Year of deglaciation (YD)	Age (2022 – YD)	Elevation [m asl]	Longitude	Latitude
p004	2008	14	2165.9	12.63944	47.12106
p010	1985	37	2159.9	12.63916	47.12163
p030	1976	46	2142.1	12.63843	47.12382
p042	1967	55	2133.1	12.63793	47.12481
p055	1955	67	2122.2	12.6368	47.12569
p073	1939	83	2110.3	12.63519	47.12712
p089	1924	98	2102.4	12.63406	47.12788
p101	1909	113	2100.1	12.63366	47.12856
p120	1882	140	2085.9	12.63384	47.12964
p126	1869	153	2083.1	12.63403	47.13017
p140	1797	225	2055.6	12.63776	47.13482

Tab A2: Full list of obtained species identities from molecular analyses of all samples collected in the field and accession numbers including published species names. OGEM refers to “Other Green Eucaryotic Microalgae”. The “per ident” values from BLAST search were appended directly to the photobiont assignments for the single haplotypes. | **Tab A2:** Vollständige Liste der Arten basierend auf molekularen Analysen aller im Feld gesammelten Proben sowie der Zugangsnummern (“accession number”) einschließlich der veröffentlichten Artnamen. OGEM steht für „Other Green Eucaryotic Microalgae“ (andere grüne eukaryotische Mikroalgen). Die „per ident“-Werte aus der BLAST-Suche wurden direkt neben den Zuordnungen der Photobionten für die einzelnen Haplotypen angefügt.

Plot	Voucher ID	Mycobiont	Trebouxia	Asterochloris	OGEM	Acc. Num. Mycobiont	Acc. Num. Photobiont
p004	UR01414	<i>Stereocaulon nanodes</i>			<i>Chloroidium saccharophilum</i> /100	PX023465	PV990947
p010	UR01415	<i>Lecidea</i> sp.	<i>Tr_</i> I01			PX023420	PV990905
p010	UR01416	<i>Rhizocarpon</i> cf. <i>geographicum</i>	<i>Tr_</i> I01/ 98.70			PX023405	PV990910
p010	UR01417	<i>Lecidea</i> sp.	<i>Tr_</i> S02/ 100			PX023421	PV990915
p010	UR01418	<i>Lecidea</i> sp.	<i>Tr_</i> S02			PX023422	PV990915
p030	UR01419	<i>Lecanora</i> cf. <i>polytropa</i>	<i>Tr_</i> I01			PX023442	PV990905
p030	UR01420	<i>Lecidea promiscens</i>	<i>Tr_</i> I01			PX023429	PV990905
p030	UR01421	<i>Bellemerea alpina</i> cf. <i>Bellemerea</i> sp.	<i>Tr_</i> S02			PX023416	PV990915
p030	UR01422	<i>Bellemerea alpina</i> cf. <i>Bellemerea</i> sp.	<i>Tr_</i> S02			PX023417	PV990915
p030	UR01423	<i>Umbilicaria aprina</i> <i>Umbilicaria</i> sp.	<i>Tr_</i> S02			PX023453	PV990915
p030	UR01424	<i>Stereocaulon alpinum</i> <i>Stereocaulon nanodes</i>			<i>Chloroidium</i> cf. <i>saccharophilum</i> /94.12	PX023466	PV990948
p030	UR01425	<i>Lecidea</i> sp.	<i>Tr_</i> I01			PX023431	PV990905
p030	UR01426	<i>Rhizocarpon</i> cf. <i>geographicum</i>	<i>Tr_</i> I01/ 99.85			PX023401	PV990907
p030	UR01427	<i>Lecidea promiscens</i>	<i>Tr_</i> I01/ 99.69			PX023432	PV990908
p030	UR01428	<i>Rhizocarpon</i> cf. <i>polycarpum</i>	<i>Tr_</i> I01			PX023406	PV990905
p042	UR01442	<i>Cladonia coniocraea</i> <i>Cladonia pyxidata</i>		<i>A. glomerata</i> /100		PX023476	PV990929
p042	UR01443			<i>A. sp.</i> <i>Vancouveria</i> <i>A588</i> /100			PV990925

Plot	Voucher ID	Mycobiont	Trebouxia	Asterochloris	OGEM	Acc. Num. Mycobiont	Acc. Num. Photobiont
p042	UR01444	<i>Lecidea promiscens</i>	<i>Tr_</i> I01/ 100			PX023423	PV990914
p042	UR01445	<i>Lecanora</i> cf. <i>polytropa</i>	<i>Tr_</i> S02			PX023446	PV990915
p042	UR01446	<i>Stereocaulon alpinum</i>		<i>A. sp.</i> Vancourova A588/99.79		PX023458	PV990917
p042	UR01447	<i>Rhizocarpon</i> cf. <i>geographicum</i>	<i>Tr_</i> I01			PX023403	PV990905
p042	UR01448	<i>Lecidea promiscens</i>	<i>Tr_</i> I01			PX023434	PV990905
p042	UR01449	<i>Lecidea promiscens</i>	<i>Tr_</i> I01	<i>A. glomerata</i> /100		PX023433	PV990905 PV990933
p042	UR01450	<i>Lecidea promiscens</i>	<i>Tr_</i> I01/ 98.70			PX023424	PV990913
p042	UR01451	<i>Stereocaulon alpinum</i>		<i>A. sp.</i> Vancourova A588/99.79		PX023459	PV990918
p042	UR01452	<i>Rhizocarpon polycarpum</i>	<i>Tr_</i> S02			PX023408	PV990915
p055	UR01429	<i>Cladonia macropyloides</i>		<i>A. glomerata</i> / 99.81		PX023473	PV990926
p055	UR01430	<i>Cladonia macropyloides</i>		<i>A. glomerata</i> /100		PX023474	PV990927
p055	UR01431	<i>Lecidea promiscens</i>		<i>A. glomerata</i> /100		PX023433	PV990922
p055	UR01432	<i>Rhizocarpon</i> cf. <i>polycarpum</i>	<i>Tr_</i> I01	<i>A. glomerata</i> /100		PX023407	PV990905 PV990928
p055	UR01433	<i>Cladonia macrophyllodes</i> <i>Cladonia macropyloides</i>		<i>A. glomerata</i> /100		PX023475	PV990935
p055	UR01434	<i>Lecidea promiscens</i>	<i>Tr_</i> I01/ 99.69			PX023427	PV990909
p055	UR01435	<i>Rhizocarpon</i> cf. <i>geographicum</i>				PX023402	
p055	UR01436	<i>Lecidea promiscens</i>	<i>Tr_</i> I01			PX023428	PV990905
p055	UR01437	<i>Lecanora</i> cf. <i>polytropa</i>	<i>Tr_</i> I01			PX023444	PV990905
p055	UR01438	<i>Bellemerea alpina</i> cf. <i>Bellemerea</i> sp.	<i>Tr_</i> I01/ 98.70			PX023414	PV990911
p055	UR01439	<i>Lecanora</i> cf. <i>polytropa</i>	<i>Tr_</i> I01			1445	PV990905
p055	UR01440	<i>Aspicilia simoensis</i>	<i>Tr_</i> I01			PX023456	PV990905
p055	UR01441	<i>Lecanora</i> cf. <i>polytropa</i>				PX023443	

Plot	Voucher ID	Mycobiont	Trebouxia	Asterochloris	OGE M	Acc. Num. Mycobiont	Acc. Num. Photobiont
p073	UR01453			<i>A. glomerata</i> /100			PV990936
p073	UR01454	<i>Cladonia ecmocyna</i>		<i>A. irregularis</i> / 100		PX023477	PV990942
p073	UR01455	<i>Stereocaulon alpinum</i>		<i>A. lobophora</i> / 99.28		PX023461	PV990921
p073	UR01456	<i>Stereocaulon alpinum</i>		<i>A. sp.</i> Vancourova A588/99.79		PX023462	PV990923
p073	UR01457	<i>Porpidia macrocarpa</i>		<i>A. stereo- caulonicola</i> /100		PX023439	PV990924
p073	UR01458	<i>Lecidea promiscens</i>				PX023425	
p089	UR01459	<i>Porpidia macrocarpa</i>		<i>A. glomerata</i> /100		PX023440	PV990937
p089	UR01460	<i>Cetraria islandica</i>	<i>Tr_ S02</i>			PX023449	PV990915
p089	UR01461	<i>Cladonia ecmocyna</i>		<i>A. irregularis</i> / 100		PX023478	PV990938
p089	UR01462	<i>Porpidia macrocarpa</i>		<i>A. irregularis</i> / 100		PX023441	PV990939
p089	UR01463	<i>Cladonia macroceras</i>		<i>A. glomerata</i> /100		PX023480	PV990931
p089	UR01464	<i>Cetraria islandica</i>		<i>A. glomerata</i> /100		PX023450	PV990930
p089	UR01465	<i>Cladonia mitis</i>		<i>A. irregularis</i> / 100		PX023471	PV990940
p089	UR01466	<i>Cladonia uncialis</i> susp. <i>uncialis</i>		<i>A. glomerata</i> /100		PX023469	PV990943
p089	UR01467	<i>Cladonia ecmocyna</i>		<i>A. glomerata</i> /100		PX023479	PV990932
p089	UR01468	<i>Stereocaulon alpinum</i>		<i>A. sp.</i> Vancourova A588/99.79		PX023460	PV990919
p089	UR01469	<i>Rhizocarpon</i> cf. <i>geographicum</i>	<i>Tr_ I01</i>			PX023404	PV990905
p089	UR01470	<i>Cladonia</i> cf.				PX023481	
p089	UR01471	<i>Cladonia squamosa</i>		<i>A. irregularis</i> / 100		PX023472	PV990941
p101	UR01403	<i>Cladonia luteoalba</i>				PX023467	
p101	UR01404	cf. <i>Bellemeria</i> sp.	<i>Tr_ S02</i>			PX023415	PV990915
p101	UR01405	<i>Lecidea</i> sp. UR01405	<i>Tr_ S02</i>			PX023435	PV990915
p101	UR01406	<i>Umbilicaria</i> sp.	<i>Tr_ S02</i>			PX023452	PV990915
p101	UR01407	<i>Lecidea lapicida</i>	<i>Tr_ S02</i>			PX023436	PV990915

Plot	Voucher ID	Mycobiont	Trebouxia	Asterochloris	OGEM	Acc. Num. Mycobiont	Acc. Num. Photobiont
p101	UR01408	<i>Lecidea promiscens</i>	<i>Tr_</i> I01			PX023426	PV990905
p101	UR01409	<i>Rhizocarpon</i> cf. <i>geographicum</i>	<i>Tr_</i> S02			PX023399	PV990915
p101	UR01410	<i>Lecidea plana</i>			<i>Pseudochlorella pyrenoidosa</i> /99.29	PX023438	PV990946
p101	UR01411	<i>Lecanora</i> cf. <i>polytropa</i>	<i>Tr_</i> S02				PV990915
p101	UR01412	<i>Stereocaulon nanodes</i>			Unknown algal isolate	PX023464	PV990949
p101	UR01413		<i>Tr_</i> I01/ 99.71				PV990906
p120	UR01472	<i>Rhizocarpon</i> cf. <i>geographicum</i>	<i>Tr_</i> S02			PX023400	PV990915
p120	UR01473	<i>Umbilicaria</i> cf. <i>umbilicarioides</i>	<i>Tr_</i> S02			PX023454	PV990915
p120	UR01474	<i>Cladonia sulphurina</i>		<i>A. glomerata</i> /100		PX023468	PV990934
p120	UR01475	<i>Lecidea promiscens</i>	<i>Tr_</i> I01/ 98.70			PX023430	PV990912
p120	UR01476		<i>Tr_</i> I01				PV990905
p120	UR01477		<i>Tr_</i> S02				PV990915
p120	UR01478	cf. <i>Bellemerea</i> sp.	<i>Tr_</i> S02			PX023418	PV990915
p120	UR01479	<i>Lecanora</i> cf. <i>polytropa</i>	<i>Tr_</i> S02			PX023448	PV990915
p120	UR01480	<i>Rhizocarpon</i> cf. <i>polycarpum</i>	<i>Tr_</i> S02			PX023409	PV990915
p120	UR01481		<i>Tr_</i> S02				PV990915
p120	UR01482	<i>Lecanora</i> cf. <i>polytropa</i>	<i>Tr_</i> S02			PX023447	PV990915
p120	UR01483	<i>Stereocaulon alpinum</i>		<i>A. lobophora</i> / 99.28		PX023463	PV990920
p120	UR01484	<i>Rhizocarpon</i> cf. <i>geographicum</i>	<i>Tr_</i> S02			PX023398	PV990915
p126	UR01394	<i>Rhizocarpon</i> cf. <i>geographicum</i>	<i>Tr_</i> I01/ 99.86			PX023396	PV990905
p126	UR01395	<i>Bellemerea</i> cf. <i>alpina</i>	<i>Tr_</i> I01			PX023410	PV990905
p126	UR01396	<i>Lecidea</i> sp.	<i>Tr_</i> I01			PX023419	PV990905
p126	UR01397	<i>Bellemerea</i> cf. <i>alpina</i>	<i>Tr_</i> I01			PX023413	PV990905
p126	UR01398	<i>Bellemerea</i> cf. <i>alpina</i>	<i>Tr_</i> I01			PX023411	PV990905
p126	UR01399	<i>Aspicilia zonata</i>	<i>Tr_</i> I01			PX023455	PV990905
p126	UR01400	<i>Rhizocarpon</i> cf. <i>geographicum</i>	<i>Tr_</i> S02/ 100			PX023397	PV990915

Plot	Voucher ID	Mycobiont	Trebouxia	Asterochloris	OGEM	Acc. Num. Mycobiont	Acc. Num. Photobiont
p126	UR01401	<i>Bellemerea</i> cf. <i>alpina</i>	<i>Tr_</i> I01			PX023412	PV990905
p126	UR01402	<i>Stereocaulon</i> <i>alpinum</i>		<i>A. sp.</i> 2709/ 99.46		PX023457	PV990916
p140	UR01485	<i>Cladonia</i> <i>arbuscula</i>		<i>A. glomerata</i> /100			PV990944
p140	UR01486	<i>Cetraria</i> <i>islandica</i>				PX023451	
p140	UR01487	<i>Cladonia</i> <i>rangiferina</i>		<i>A. glomerata</i> /100		PX023470	PV990945

Myco-, photobiont and bacterial microbiome associations along an elevational gradient in the Hohe Tauern, Salzburg, Austria

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Lichens are among the few organisms capable of thriving in extreme environments, forming miniature ecosystems composed of diverse fungal, algal, and bacterial communities. To characterize their symbiotic community structure along climatic gradients, the composition, distribution, and interactions of their primary symbiotic partners (mycobiont [fungus]/ photobiont [algae]) and the bacterial microbiomes were studied. Using molecular techniques, including Sanger and high-throughput amplicon sequencing, we analyzed saxicolous lichens along an elevational gradient (1168–2562 m a.s.l.) in the Grossglockner region, Salzburg, Austria.

The following research questions were addressed: (i) Do the symbiotic partners of lichens – mycobionts, photobionts, and bacterial communities – vary in composition and diversity along an elevational gradient? (ii) Do lichens at the same site share locally available symbiotic partners, such as photobionts, and bacterial microbiomes?

All three partners of lichen communities, i.e. mycobionts, photobionts, and bacteria, varied in diversity and composition along the elevational gradient. Neighboring lichens within microhabitats shared photobionts, indicating local availability as a key factor in partner selection. However, bacterial microbiomes showed substantial heterogeneity across and within sites, influenced by mycobiont-photobiont interactions. The formation of local guilds drives new symbiotic combinations that may improve the adaptability of lichens to environmental changes and the colonization of new niches.

Mittag M, Junker RR, Ruprecht U (2026) Assoziationen von Myko-, Photobionten- und Bakterienmikrobiom entlang eines Höhengradienten in den Hohen Tauern, Salzburg, Österreich

Flechten gehören zu den wenigen Organismen, die in der Lage sind, auch in extremen Umgebungen zu gedeihen und formen Miniatur-Ökosysteme, die aus verschiedenen Pilz-, Algen- und Bakteriengemeinschaften bestehen. Zur Charakterisierung ihrer Gemeinschaftsstruktur entlang klimatischer Gradienten analysierten wir die Zusammensetzung, Verteilung und Interaktionen ihrer Symbiosepartner und Mikrobiome mit molekularen Techniken wie Sanger- und Next-Generation-Sequenzierung. Die Studie fokussierte sich auf felsbewohnende Flechten entlang eines Höhengradienten (1168–2562 m ü. NN) in der Großglocknerregion, Österreich.

Im Rahmen der vorliegenden Studie wurden folgende Forschungsfragen untersucht:

(i) Lassen sich Veränderungen in der Zusammensetzung der Symbiosepartner von Flechten – Mykobionten, Photobionten und bakterielle Mikrobiome – entlang eines Höhengradienten beobachten? (ii) Teilen sich Flechten am selben Standort die lokal verfügbare symbiotische Partner, wie Mykobionten, Photobionten und Mikrobiome?

Die Ergebnisse zeigen deutliche Veränderungen der Flechtengemeinschaften und ihrer Symbiosepartner entlang des Höhengradienten. Innerhalb einzelner Mikrohabitate teilen benachbarte Flechten häufig Photobionten, was auf lokale Verfügbarkeit als entscheidenden Faktor hinweist. Mikrobiome zeigen jedoch beträchtliche Heterogenität zwischen und innerhalb der beprobten Areale, beeinflusst durch Mykobionten-Photobionten-Assoziationen. Die Bildung lokaler Gildenstrukturen erlaubt die Etablierung neuartiger symbiotischer Kombinationen von Flechten und ihren assoziierten Partnern. Dies könnte ihre für ihre Adaptionsfähigkeit an Umweltveränderungen sowie für die Besiedlung neuer ökologischer Nischen von Vorteil sein.

Keywords: Saxicolous crustose lichens, symbiotic associations, photobionts, mycobionts, bacterial microbiomes, molecular ecology, elevational gradient.

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Introduction

Lichens represent intricate symbiotic systems including fungi and photosynthetic partners, such as algae or cyanobacteria, as well as other fungi, algae and bacteria which interact closely, enabling them to thrive in a wide range of environmental conditions (Aschenbrenner et al. 2016; Hawksworth & Grube 2020; Goodenough & Roth 2021; Morillas et al. 2022). Over the past 600 million years, lichens have demonstrated remarkable persistence, colonizing some of the most extreme environments on Earth, from arid deserts to polar areas (Galloway 2008; Thüs & Schultz 2009). Understanding the association patterns of lichens in relation to environmental conditions is fundamental for identifying the drivers of lichen biodiversity across all symbiotic components (Briggs & Walters 2016; Spribille et al. 2022).

While lichens can thrive in a broad range of environmental conditions, their actual occurrence is scale-dependent, shaped by microhabitat conditions at fine scales as well as regional climate factors at broader scales. Thus, some lichen guilds show similar community structures across sites with comparable microhabitat conditions, regardless of differences in broader climatic settings (Peksa et al. 2022). Despite current gaps in comprehensive knowledge of lichen diversity and the relationships between the mycobiont (fungus) and the photobiont (algae), documented regional occurrences indicate that climate, with its main factors such as temperature, precipitation patterns, wind, and solar radiation, also significantly influences the distribution of photobionts and thus the ability to adapt to external stress factors (Wagner et al. 2020; Rolshausen et al. 2023).

The core of the lichen symbiosis consists of a dominant mycobiont and photobiont partner, the latter typically green algae and/or cyanobacteria, embedded in a bacterial layer with biofilm-like structures (Grube et al. 2009; Bates et al. 2011; Aschenbrenner et al. 2014). In addition to these main partners, lichens host a multitude of further symbionts, including diverse communities of endolichenic and lichenicolous fungi, basidiomycetous yeasts (Lawrey & Diederich 2003; Arnold et al. 2009; Spribille et al. 2022), several green algal (Guzow-Krzemińska 2006; Peksa & Škaloud 2011) as well as diverse bacterial communities (Grube & Berg 2009; Bates et al. 2011). This assemblage forms a highly integrated miniature ecosystem with complex interactions among fungal, algal, and bacterial components (Aschenbrenner et al. 2014). Recent studies describe lichens as holobionts, integrated biological units comprising a host and microbiota. Mycobionts, typically Ascomycota, sometimes Basidiomycota, directly expose their mycelium to environmental conditions. They contribute to structural integrity and stress protection, while photobionts, through photosynthesis, supply energy-rich compounds. Bacterial components, often forming biofilms

on fungal surfaces, perform key functions such as nitrogen fixation, pathogen defense, and growth regulation (Grube et al. 2015; Auður Sigurbjörnsdóttir et al. 2016). In addition, the poikilohydric lifestyle of lichens enables them to survive in prolonged drought, which allows for their persistence in challenging habitats such as alpine regions or the extreme cold areas of the Antarctic Continent (Schroeter et al. 2010). Furthermore, these complex microbial consortia appear to be shaped by both environmental filtering, co-dispersal, and co-evolutionary processes (Fernández-Mendoza et al. 2011; Aschenbrenner et al. 2014; Spribille et al. 2022).

The phenomenon of anthropogenic climate change has been observed to accelerate several environmental transformations, including geographic range shifts, alterations to species interactions, and a reduction in biodiversity (Thomas et al. 2004; Tylianakis et al. 2008; Pecl et al. 2017). Alpine ecosystems are particularly susceptible to the effects of climate change, with rising temperatures driving vegetation shifts to higher altitudes and reducing the availability of niches for species at lower elevations, thereby increasing extinction risks (Pörtner et al. 2022). Understanding these dynamics is essential to predicting and mitigating biodiversity loss in the face of rapid environmental change (Leclère et al. 2020; Pörtner et al. 2022; Pfenning-Butterworth et al. 2024; Götz et al. 2026).

Elevational gradients provide a valuable framework for studying lichen ecology and the impacts of climate change. These gradients serve as proxies for climatic variability, revealing insights into species distribution patterns and their adaptive capacities. For instance, lichens exhibit significant turnover in myco-/photobiont associations along elevational transects, suggesting that environmental filtering and niche specialization play crucial roles in shaping community assemblages (Dal Grande et al. 2017; Rolshausen et al. 2023). Observations from genomic and community studies indicate that compositional shifts in lichen symbioses often coincide with regional climatic transition zones (Rolshausen et al. 2023).

The Großglockner Mountain range in the Austrian Alps represents a valuable site for investigating biodiversity and climate interactions. Spanning diverse climatic zones, from montane beech-spruce forests to nival zones of snow and ice, this region provides distinct ecological niches shaped by factors such as temperature, precipitation, and microclimatic variability (Grabherr et al. 2010). Recent studies have highlighted significant temperature increases and altered precipitation patterns in the region, influencing species composition and ecosystem structure (Taucher et al. 2009).

This study aims to assess the distribution and diversity of the dominant mycobiont and photobiont as well as bacterial microbiome associations in rock-dwelling lichens along an elevational gradient (1168–2562 m a.s.l.) along the Grossglockner High Alpine Road (Salzburg, Austria), to analyze the influence of climatic factors on lichen communities and evaluate the potential of lichens as bioindicators for climate change. This work will contribute to understanding the dynamics of biodiversity under changing climatic conditions, with implications for conservation and management strategies.

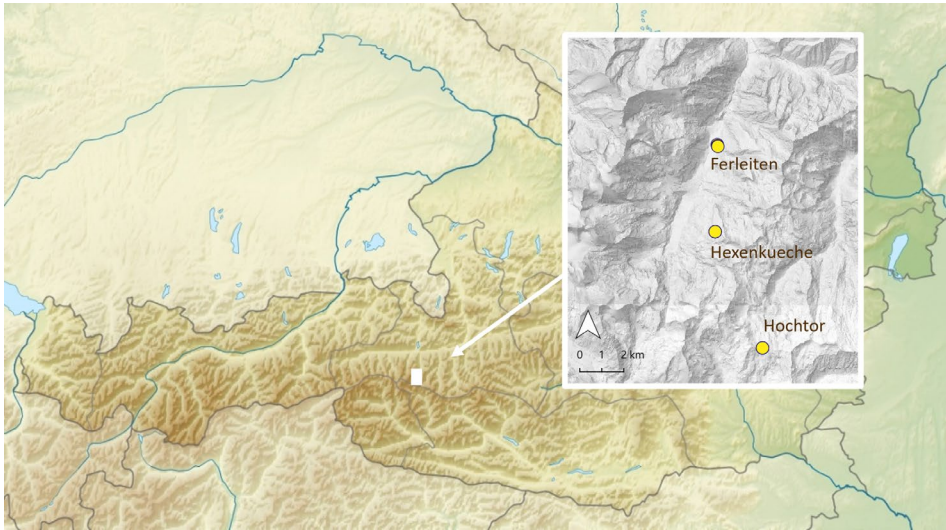


Fig. 1: Topographic Map of Austria. The rectangle indicates the position of the study area within Austria. The insert shows a detailed topographic view of the sampling region in Salzburg, Hohe Tauern, with individual sampling sites marked by yellow circles: Ferleiten, 1168 m a.s.l., Hexenküche, 2153 m a.s.l., Hochtör, 2562 m a.s.l. Source: CC / Uwe Dederling. | **Abb. 1:** Topographische Übersichtskarte von Österreich mit Markierung und Detailsansicht des Untersuchungsgebiets in Salzburg, Hohe Tauern. Die Untersuchungsgebiete sind durch gelbe Kreise gekennzeichnet: Ferleiten, 1168 m Seehöhe, Hexenküche, 2153 m, Hochtör, 2562 m. Quelle: CC / Uwe Dederling.

Materials and Methods

Long Term Lichen Diversity Experiment (LTLDE)

This work is the basic survey of all existing lichens at the LTLDE observation sites and provides baseline data for tracking succession processes over a ten-year period. The long-term project “LTLDE: Long Term Lichen Diversity Experiment,” initiated in 2017, aims to monitor the succession and recolonization dynamics of lichen-associated organism groups annually after complete removal. As part of the project, a comprehensive molecular evaluation of the internal diversity of 103 lichen samples was conducted at T0, the project start, as shown in Fig. S1. These samples were collected from three sites along an elevational gradient on the Grossglockner High Alpine Road in Austria, see Fig. 1, focusing on the diversity of the dominant myco-, photobionts and the bacterial microbiome and their associations.

Sampling

Lichen community samples were collected at three sampling sites along an elevation gradient during the month of August 2017. For each site, three approx. 30 x 20 cm rocks were removed and transported to the laboratory to assign the lichen samples present on the rock with molecular techniques. All sites were located on the Grossglockner High Alpine Road, Austria.

At 1168 m a.s.l. Ferleiten (F), N 47.16536/ E 012.81457, represents the lowest site along the elevational gradient. The site is located below the treeline and frequent agricultural use for grazing may result in elevated nitrogen levels. As with the first sampling site, three rock fragments were taken from the second sampling site, Hexenküche (He), at 2153 m above sea level, N 47.12968/ E 012.81369. It is located approximately at the tree line and is rarely used as pasture for sheep and cattle. Hochtor (H), N 47.08228/ E 012.84254, is the highest site in this study at 2562 m above sea level, Tab. S1. As with the previous sampling sites, three rock fragments were collected here. The vegetation is dominated by biological soil crusts and saxicolous plant and lichen communities. Livestock grazing is relatively rare. Mean annual temperature and precipitation data for the three sampling sites are available at GeoSphere Austria (formerly the Central Institute for Meteorology and Geodynamics, ZAMG; <https://www.geosphere.at>).

A total of 103 lichen samples were collected across all rock replicates by scraping organic material from the center of each thallus into (1) Eppendorf tubes for the mycobiont and photobiont analyses and (2) tubes for stabilizing the bacterial communities, using a sterilized scalpel. All samples were stored at minus 20° Celsius.

DNA extraction of mycobiont, photobiont and the bacterial microbiome

For extraction and isolation of genomic DNA of the lichen specimens, the DNeasy® Plant Mini Kit (Qiagen) was used according to the manufacturer's instructions. To disrupt the tissue, the Eppendorf tubes containing the samples were ground with micro pestles in liquid nitrogen. All bacterial samples were extracted and provided by the LTLDE project group 2017 using the Xpedition Fungal/Bacterial DNA MiniPrep following the manufacturer's instructions (Zymo Research).

Sanger Sequencing (Myco-/photobiont) and amplicon generation/sequencing (bacterial microbiome)

The widely used barcode marker Internal Transcribed Spacer (ITS) was amplified and sequenced for both symbiotic partners in order to detect the available species. For the mycobiont the primers ITS1F (Gardes & Bruns 1993) and ITS4 (White et al. 1990) and for the photobiont ITS1T and ITS4T (Trebouxia, Kroken & Taylor 2000) and ITS-sense-A and ITS-antisense-A (Ruprecht et al. 2014), as well as nr-SSU-1780-5' (Piercey-Normore & DePriest 2001) and ITS4 were used according to Ruprecht et al. (2020), as shown in Tab. S3. For the bacteria the v3v4 region of the bacterial rRNA gene was amplified with standard primers provided by Eurofins. Sanger sequencing as well as Illumina sequencing and analysis of the bacterial microbiome composition was done at Eurofins Genomics in Germany.

Taxonomic identification

The final sequences of the mycobionts' and photobionts' nuclear ITS region were assembled and edited with Geneious version 6.1.8 (Kearse et al. 2012) and aligned with Geneious Alignment and MAFFT v7.017 (Katoh et al. 2002). The Basic Local Alignment Search Tool (BLAST) of the National Library of Medicine/National Centre of Biotechnology

and Information (NCBI) database (Altschul et al. 1990) was employed to facilitate the comparison of each mycobiont sequence with the international database for the purpose of identification. Further mycobiont sequences of the genera *Lecidea* Ach. and *Porpidia* Körb. as well as the photobiont sequences of the genera *Asterochloris* Tschermak-Woess and *Trebouxia* Puymaly were compared with those previously generated by Ruprecht et al. (2020) and Muggia et al. (2020), which formed the basis for the corresponding taxonomic classification.

Diversity indices

Alpha, beta and gamma diversity of mycobionts, photobionts and bacterial microbiomes were calculated as Hill numbers of order $q = 1$, equivalent to the exponential of Shannon entropy, using the R package *entropart* (Marcon & Hérault 2015). This measure weights species by their relative abundance and is less sensitive to rare species than species richness ($q = 0$). Estimation bias was corrected using the “Best” estimator as implemented in *entropart*. Prior to diversity calculation, bacterial count data were rarefied to a minimum sequencing depth of 1040 reads using the R package *rtk* (Saary et al. 2017), to account for unequal sequencing effort across samples. Diversity was calculated separately for each of the three symbiotic components, mycobionts, photobionts and bacterial microbiomes, and compared across the three sampling sites (Ferleiten, Hexenküche, Hochtor).

Statistical analyses

Statistical analyses were performed using R version 4.3.2. To visualize differences in the species composition and the associated partners we used non-metric multidimensional scaling (NMDS) plots produced with the *metaMDS* function in R package *vegan* (Oksanen et al. 2022) based on Bray-Curtis dissimilarity values with a maximum of 100 random starts and three dimensions. The *ggvenn* function in the R package *ggvenn* (Yan 2025) was used to graphically represent species distributions for mycobionts, photobionts, and bacteria based on the number of species shared between sites. As an unconstrained ordination approach based on a dissimilarity matrix, several calculations were performed using a distance-based redundancy analysis (db-RDA) with the *capscale*-function in R package *vegan*. A network of all associated Taxa and OTUs of the mycobionts and photobionts was conducted using the Gephi interactive platform and the Force Atlas continuous layout algorithm (Bastian et al. 2009). A complete species list is provided in the Supplementary Information: (Tab. S2 and App. 1/2).

Bipartite network and network indices

To visualize the ecological network patterns between mycobiont, photobiont, and the bacterial microbiome of the dataset, bipartite diagrams were created using the *plotweb()* function provided in the R-package *bipartite* (Dormann et al. 2008). The network descriptive indices H_2' and d' (Blüthgen et al. 2006) were calculated using the function *H2fun()* and *dfun()*. When determining the level of specialization H_2' describes the complementary specialization of all interacting groups. H_2' becomes larger with increasing selectivity of a species. d' can range from zero to one, where one means a complete specialist in terms of available association partners at the higher level. It determines how divergent a species group is compared to a random sample of available interaction or association partners.

Results

Taxonomic classification and spatial distribution

A total of 103 lichen specimens were sampled, of which 80 had sequence data available for all three symbiotic partners (mycobiont, photobiont, and bacterial microbiome). Altogether 32 dominant mycobiont species belonging to ten families were determined, with associated photobionts distributed among six operational taxonomical units (OTUs) of the genera *Trebouxia* and *Asterochloris*, hereafter abbreviated as *Tr* and *Ast*, respectively. In total, bacteria belonging to 114 families were detected, of which 110 were retained after CSS-normalization

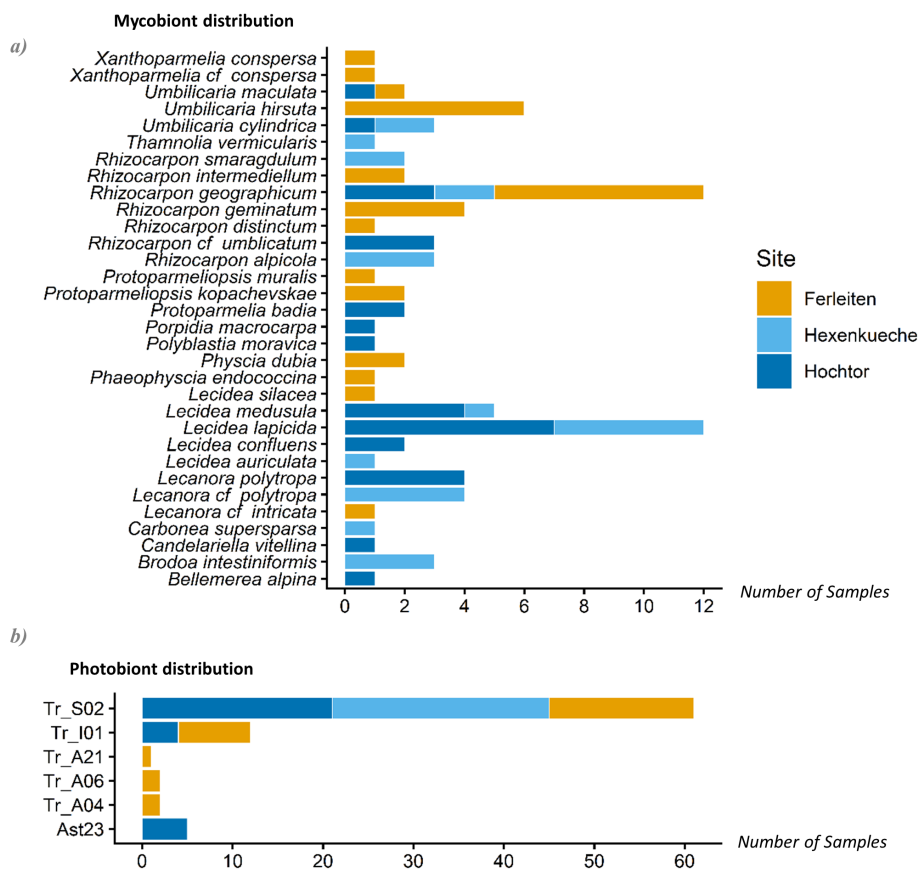


Fig. 2: Distribution of mycobiont species and photobiont OTUs across the sites Ferleiten, Hexenküche and Hochtör along the Großglockner High Alpine Road, Austria. Bars show the number of samples of each identified species/OTU, colour-coded by site: **a)** mycobionts, **b)** photobionts. | **Abb. 2:** Verteilung der Mykobionten-Arten und Photobionten-OTUs in den Untersuchungsgebieten Ferleiten, Hexenküche und Hochtör entlang der Großglockner Hochalpenstraße, Österreich, basierend auf insgesamt 103 saxicolen Flechtenproben. Dargestellt ist die summierte Häufigkeit pro Art bzw. OTU an den farbco-dierten Standorten für **a)** Mykobionten und **b)** Photobionten.

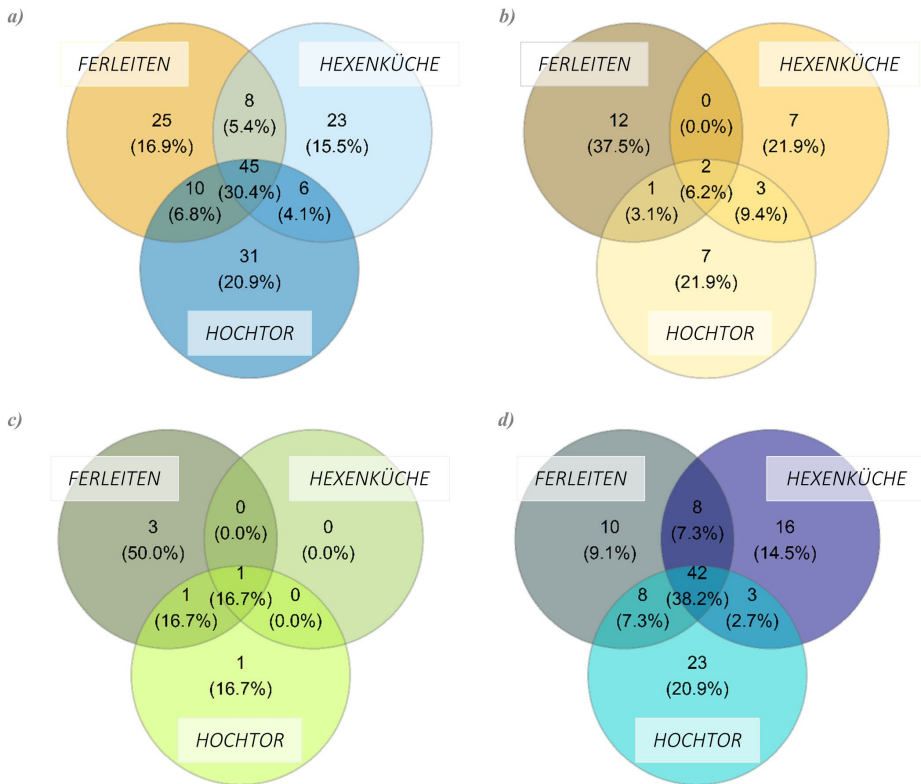


Fig. 3: Venn diagram showing species distribution by the numbers of species shared between the three sites, ranging from 1160 to 2750 m above sea level. **a)** All dominant symbiotic partners, **b)** mycobiont, **c)** photobiont, **d)** bacteria. | **Abb. 3:** Venn-Diagramme zur Artenverteilung zwischen den drei Untersuchungsstandorten entlang des Höhengradienten (1160–2750 m ü. d. M.). Dargestellt ist die Anzahl gemeinsam vorkommender Arten von **a)** allen dominanten symbiotischen Partnern, **b)** Mykobionten, **c)** Photobionten und **d)** bakteriellen Taxa.

and used in downstream analyses. All mycobiont species and photobiont OTUs present are listed in Fig. 2 and color-coded according to their location. Fig. 3a-d shows the species distribution between all three sampling sites at different elevations. The most common species among mycobionts were *Rhizocarpon geographicum* (L.) DC. and *Lecidea lapicida* (Ach.) Ach. and the most common photobiont was OTU *Tr_S02*. *Rhizocarpon geographicum* is also the only mycobiont species observed at all three sites as well as the photobiont OTU *Tr_S02*. Occurrences of mycobiont species and photobiont OTUs exclusively observed at one site are shown in Fig. 2a and Fig. 3b and c.

All three sampling sites along the altitudinal gradient did not differ significantly in their species/OTU composition of mycobionts, photobionts and bacteria. A permutational multivariate analysis of variance (PERMANOVA) based on Bray-Curtis dissimilarity with 999 permutations showed that elevation accounted for approximately 32% of the variance in

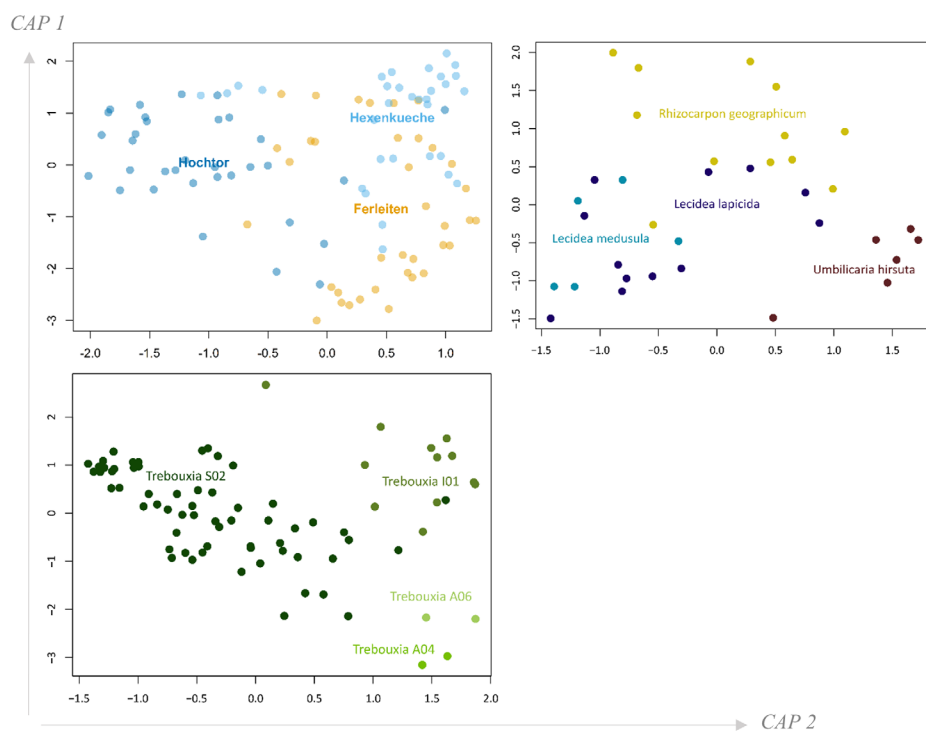


Fig. 4: CAP – Distance-based Redundancy Analysis. Permutation test (capscale under reduced model, anova: m1, by="term", permutations=1000) of the composition of the bacterial communities (OTUs on family level): **a)** along the elevational gradient, **b)** in relation to the dominant mycobiont species ($n \geq 5$), **c)** the most common photobiont OTUs ($n \geq 2$). | **Abb. 4:** CAP – Distanzbasierte Redundanzanalyse (db-RDA) zur Zusammensetzung des bakteriellen Mikrobioms (OTUs auf Familienebene), basierend auf einem Permutationstest (capscale, reduziertes Modell, anova: m1, by= „term“, 1000 Permutationen): **a)** entlang des Höhengradienten, **b)** in Bezug auf die dominanten Mykobiontenarten ($n \geq 5$), **c)** in Bezug auf die häufigsten Photobionten-OTUs ($n \geq 2$).

overall community composition ($R^2 = 0.317$), an effect that was not statistically significant ($F_{2,6} = 1.392$, $p = 0.125$; see Tab. S4).

Because of the unconstrained ordination approach based on a dissimilarity matrix, several further calculations were performed using a distance-based redundancy analysis (db-RDA). The results show significant differences in bacterial microbiome composition between sampling sites ($F_{2,99} = 5.143$, $p < 0.001$; Fig. 4a). In addition, the composition of the bacterial microbiome was significantly influenced by the identity of the mycobiont species ($Df = 3$, $F = 1.668$, $p = 0.017$, $n \geq 5$; see Fig. 4b) and the photobiont OTUs ($Df = 3$, $F = 2.863$, $p < 0.001$; see Fig. 4c; Tab. S5). The overall bacterial microbiome was dominated by *Acidobacteriaceae*, followed by *Acetobacteraceae* and *Solibacterales*. When testing individual rock replicates at each sampling site for differences in bacterial community composition, a significant effect of replicate identity was detected ($F_{8,93} = 3.657$, $p < 0.001$; Fig. 5, Tab. S6).

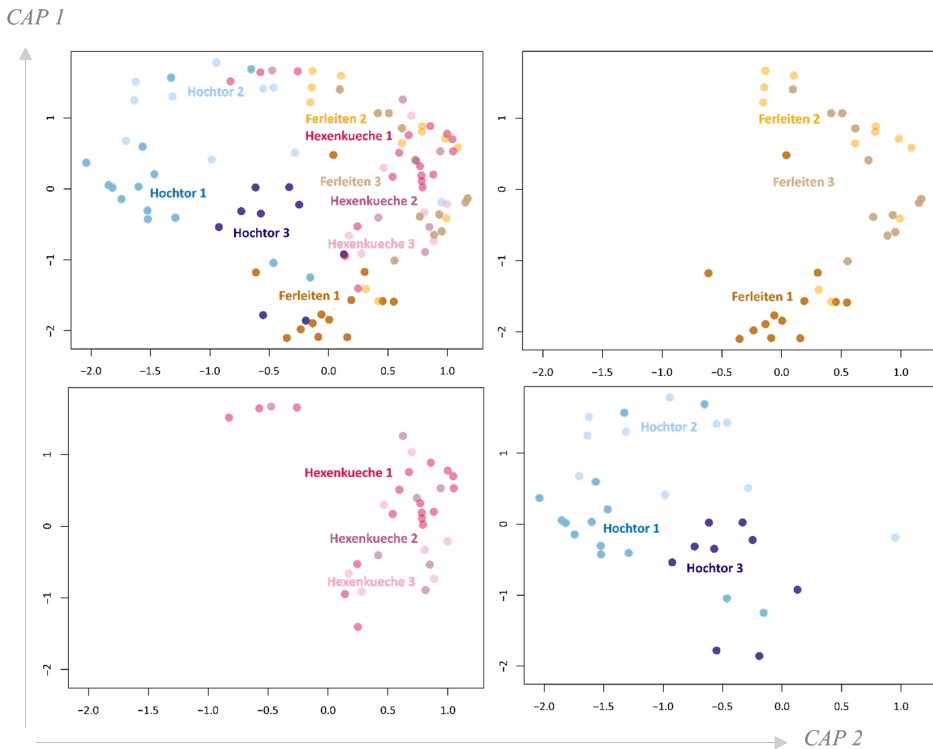


Fig. 5: CAP – Distance-based Redundancy Analysis for the single replicates. Permutation test (capscale under reduced model, anova: m1, by="term", permutations=1000) of the composition of the bacterial communities at **a)** all areas, **b)** Ferleiten, **c)** Hexenküche and **d)** Hochtör. | **Abb. 5:** CAP – Distanzbasierte Redundanzanalyse (db-RDA) zur Zusammensetzung des bakteriellen Mikrobioms auf Ebene einzelner Replikate, basierend auf einem Permutationstest (capscale, reduziertes Modell, anova: m1, by = „term“, 1000 Permutationen): **a)** alle Untersuchungsgebiete kombiniert, **b)** Ferleiten, **c)** Hexenküche und **d)** Hochtör.

Diversity indices

Alpha diversity was highest at Ferleiten for both the photobiont and bacterial microbiome communities (photobiont: 3.555; bacterial microbiome: 7.127), based on Hill numbers calculated from OTU abundance data. For mycobionts, alpha diversity was comparable at Ferleiten (15.139) and Hochtör (15.603), with a marked decrease at the intermediate site Hexenküche (12.207). For the bacterial microbiome, alpha diversity decreased continuously with elevation (Ferleiten: 7.127; Hexenküche: 5.504; Hochtör: 4.576). The photobiont community at Hexenküche showed the lowest alpha diversity (1.000), consistent with only a single photobiont OTU recorded at this site (Fig. 2), with a slight increase at Hochtör (2.264). Beta diversity was higher for mycobionts (1.926) than for photobionts (1.252), indicating greater compositional turnover among mycobionts across sites, which partly reflects the substantially larger species pool of mycobionts compared to photobiont OTUs.

Tab. 1: Diversity indices – Alpha, Beta and Gamma Diversity – of the community composition of Lichen associated species, mycobiont, photobiont and bacterial microbiome along three elevational steps (Ferleiten, Hexenküche and Hochtor) at the Großglockner High Alpine Road, Austria. | **Tab. 1:** Diversitätsindizes – Alpha-, Beta- und Gamma-Diversität – der Artenzusammensetzung von Flechtenassoziierten Arten, Mykobionten, Photobionten und dem bakteriellen Mikrobiom entlang dreier Höhenstufen (Ferleiten, Hexenküche und Hochtor) entlang der Großglockner-Hochalpenstraße, Österreich.

	All	Mycobiont	Photobiont	Microbiome
Alpha Diversity (Hill numbers, q = 1)				
Ferleiten	7.132	15.139	3.555	7.127
Hexenküche	5.507	12.207	1.000	5.504
Hochtor	4.580	15.603	2.264	4.576
Beta Diversity	1.188	1.926	1.252	1.188
Gamma Diversity	6.709	21.176	2.393	6.704

Gamma diversity was similarly higher for mycobionts (21.176) than for photobionts (2.393), reflecting both a broader regional species pool and the higher total number of mycobiont species recorded (Tab. 1).

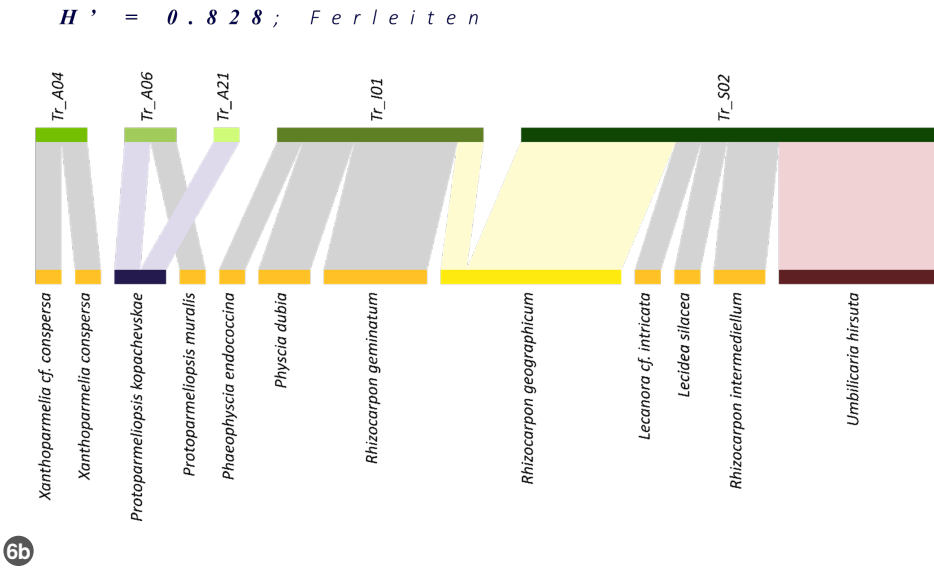
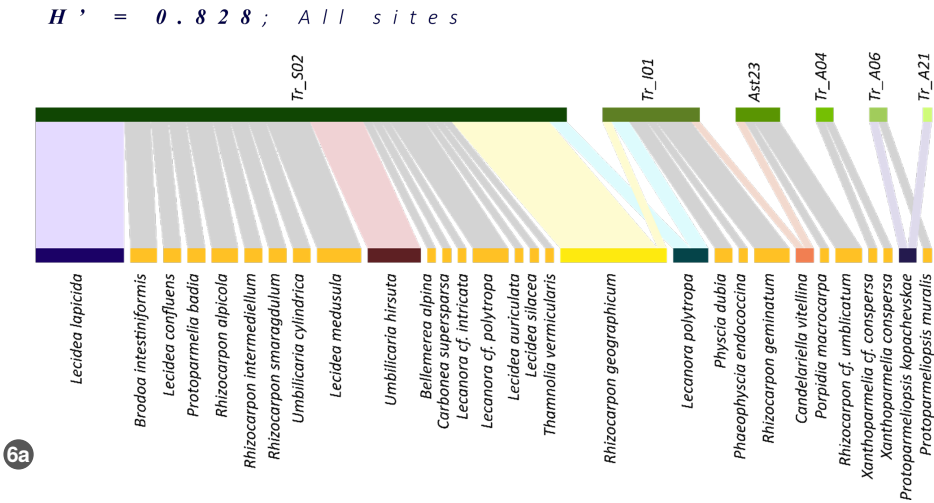
Network analysis

Interaction networks were analyzed for all symbiotic associations between mycobiont species (first level) and the corresponding photobiont OTUs (second level) and visualized with bipartite networks. The graphs represent all study sites and each site individually (Fig. 6 a-d). The overall degree of specialization of the mycobionts is comparatively high at the sites where it could be quantified. At Hochtor, an H2' value of 0.760 indicates a network with predominantly specialized interactions between symbiotic partners, while Ferleiten, as the lowest sampling site, has an H2' value of 0.828. Hexenküche contains only one photobiont, *Tr_S02*, across all replicates. While the majority of fungal symbionts interact exclusively with one photobiont, several exceptions were observed: *Protoparmeliopsis kopachevskae* associates with both *Tr_A06* and *Tr_A21*, and *Candelariella vitellina* with both *Ast23* and *Tr_I01* (Fig. 6). Note that *Lecanora cf. polytropa* and *Lecanora polytropa* are treated as separate taxa here, although a conspecific relationship cannot be excluded based on morphological evidence alone. In contrast to the highly specialized mycobiont photobiont networks, the mycobiont microbiome networks showed consistently low specialization at all three sites (H2' = 0.188 / 0.135 /0.444).

Lichen Guilds

To provide an overview of which lichens share the same photobionts, and which are associated with others, mycobiont species and photobiont OTUs were color-coded (see Fig. 7). Of all nine replicates, five contained only one photobiont, *Tr_S02*, which was shared by all the available mycobionts and was abundant on all three elevational steps.

This was the case for all replicates from Hexenküche and two replicates from Hochtor, containing 57 samples with 16 mycobiont species. The samples from Ferleiten comprise



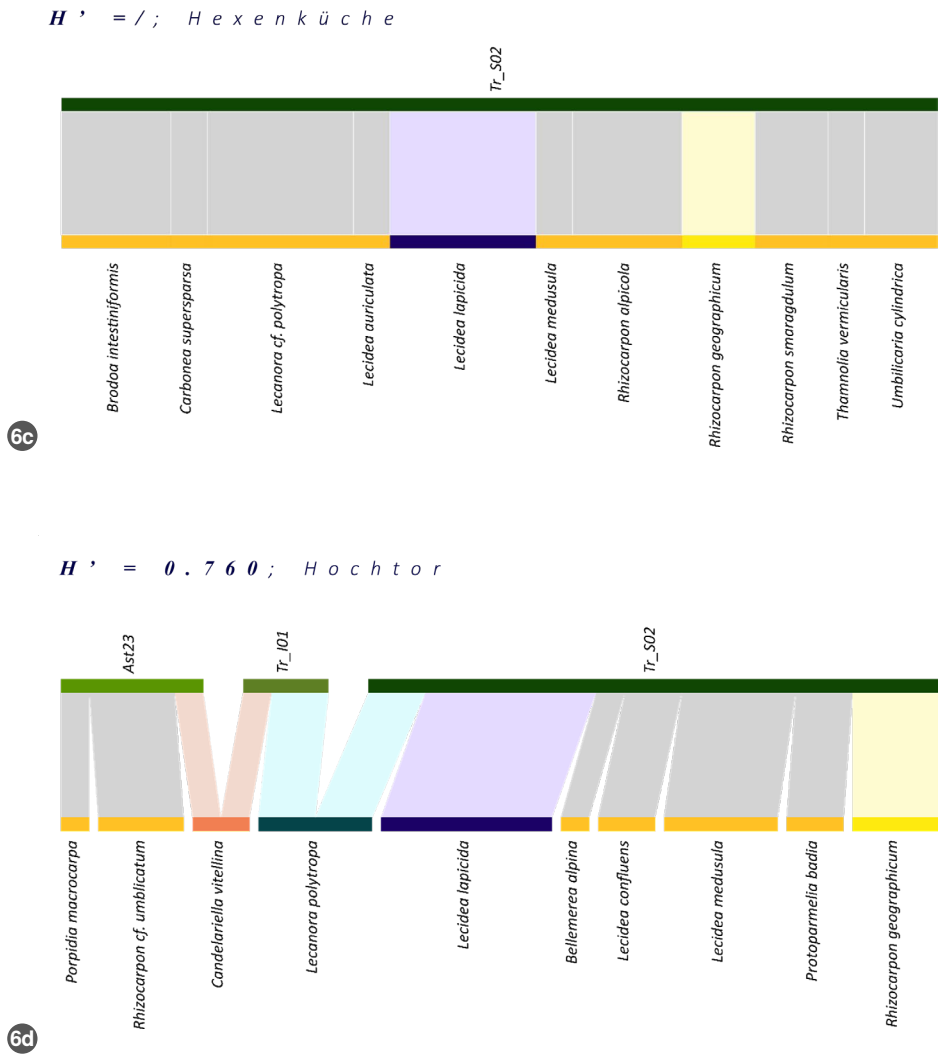


Fig. 6: Bipartite networks for the associated mycobiont species and photobiont OTUs at all three sampling sites. Samples were taken at the Großglockner High Alpine Road, Austria: **a)** all sites, **b)** Ferleiten, **c)** Hexenküche, **d)** Hochtor. For each network the H_2' -Value is calculated. Rectangle width is according to the frequencies of species and OTUs. Interactions are graphically displayed by lines connecting photobionts and mycobionts. The width of the lines is proportional to the number of accessions. | **Abb. 6:** Bipartite Netzwerke der Assoziationen zwischen Mykobionten-Arten und Photobionten-OTUs an den drei Untersuchungsstandorten entlang der Großglockner Hochalpenstraße, Österreich. **a)** Alle Standorte, **b)** Ferleiten, **c)** Hexenküche, **d)** Hochtor. Für jedes Netzwerk ist der H_2' -Wert als Maß für die Netzwerkstruktur angegeben. Die Breite der Rechtecke entspricht der relativen Häufigkeit der jeweiligen Taxa/ OTUs; vertikale Linien zeigen Interaktionen, deren Dicke proportional zur Anzahl dokumentierter Zuordnungen ist.

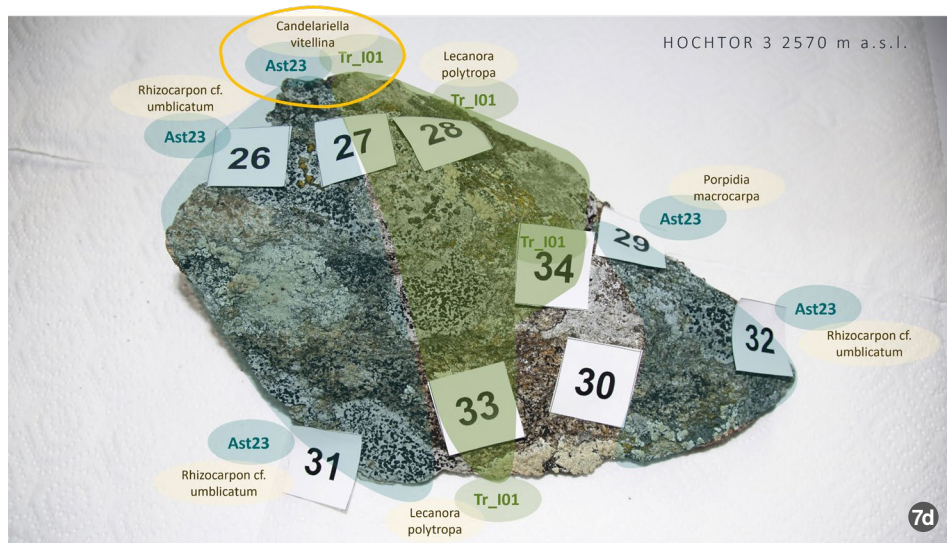
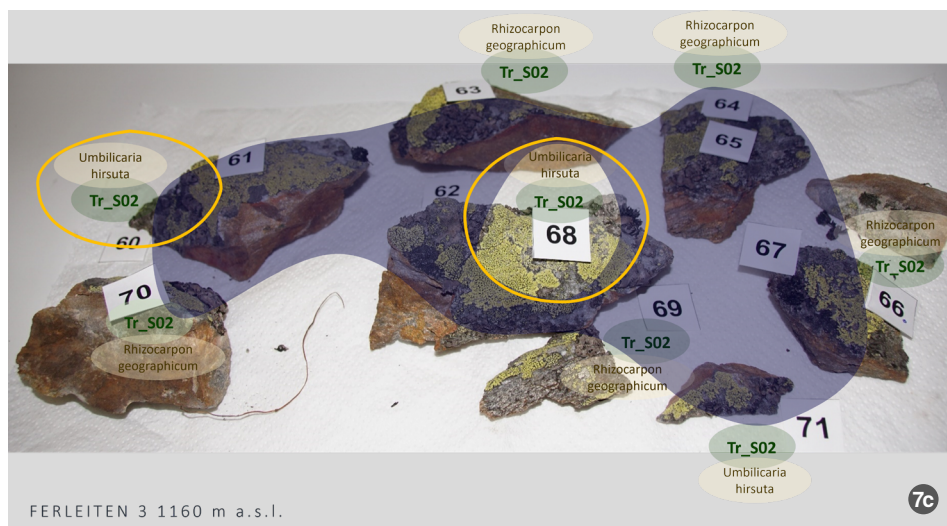


Fig. 7: Images and simplified representation of the replicates and the occurring mycobiont species and photobiont OTUs. Only four of nine replicates are shown, as only one common photobiont occurs on all other five replicates He01, 02, 03, H01, 02. The interacting species are listed side by side. The spatial distribution of the photobiont is represented by color-coded areas. Species that appear to be associated with more than one photobiont in a replicate are circled. Sampling area: Großglockner High Alpine Road, Austria. | **Abb. 7:** Darstellung ausgewählter Replikate mit visualisierten Symbionten Assoziationen sowie Auflistung der nachgewiesenen Mykobionten-Arten und Photobionten-OTUs. Gezeigt werden vier von insgesamt neun Replikaten; die übrigen fünf wurden aufgrund des Vorkommens nur eines gemeinsamen Photobionten nicht berücksichtigt. Interagierende Arten sind paarweise angeordnet, die räumliche Verteilung der Photobionten erfolgt mittels farblicher Codierung. Individuen mit multiplen Photobionten-Assoziationen sind durch eine Umrahmung hervorgehoben. Untersuchungsgebiet: Großglockner Hochalpenstraße, Österreich.

five different photobiont OTUs, all belonging to the genus *Trebouxia*, *Tr_A06*, *Tr_A21*, *Tr_I01*, *Tr_A04*, and *Tr_S02*. There are four different photobiont OTUs in F1 (Ferleiten replicate no. 1), two in F2, and one in F3, with *Tr_S02* being the only OTU present across all three replicates. Hochtor (highest elevational step on the gradient) contains three different photobiont OTUs, of which one belongs to the genus *Asterochloris* (*Ast23*), alongside *Tr_S02* and *Tr_I01*. *Tr_I01* and *Tr_S02* are the only photobionts found at both the lowest and highest sampling sites.

In general, it is notable that *Tr_S02* exhibits the largest number of associations. Other OTUs, including *Tr_A21*, *Tr_A06*, and *Tr_A04*, occur less frequently and are exclusively found at Ferleiten. *Ast23* is present only at Hochtor, while *Tr_I01* and *Tr_S02* are distributed across multiple sites. However, further sampling is needed to draw definitive conclusions about site-specific clustering of photobiont associations.

Discussion

Due to the dominance of lichens in extreme environments such as rock surfaces and high alpine areas in general as well as their variable symbiont associations along climatic (elevational) gradients (Rolshausen et al. 2023), they are very useful for the investigation of climate change scenarios (Sancho et al. 2019; Wagner et al. 2021).

Our findings indicate that the composition of mycobionts, photobionts, and bacterial microbiomes is shaped by factors associated with elevation, likely reflecting underlying environmental gradients and partner availability, although no direct climatic measurements were included.

Variation in Symbiotic Associations Along an Elevational Gradient

While mycobiont assemblages exhibited high site specificity with limited overlap between elevations, photobiont composition was dominated by a few widely distributed OTUs, notably *Tr_S02*, which occurred across all sites. This aligns with previous findings suggesting that fungal symbionts exhibit stronger habitat turnover, whereas photobionts often act as broadly distributed generalists (Dal Grande et al. 2018; Ruprecht et al. 2020; Wagner et al. 2020; Rolshausen et al. 2023). In contrast, the *Asterochloris* OTU *Ast23* was restricted to high elevations, supporting the view that photobiont distributions can reflect niche specialization under specific environmental constraints (Peksa & Škaloud 2011; Wagner et al. 2020).

Moreover, many symbiotic pairings were unique to individual sites. This spatial partitioning of symbiotic associations supports the hypothesis of environmentally structured guilds (Peksa et al. 2022). Previous studies show that species within the genus *Trebouxia* exhibit varying degrees of altitudinal preference, with some lineages showing clear ecological specialization (Dal Grande et al. 2018), which aligns with our observation that certain mycobiont species associate with more than one photobiont OTU across sampling sites. Notably, mycobionts with lower photobiont specificity, as exemplified by the wide geographical and climatic range of *Cetraria aculeata* (Fernández-Mendoza et al. 2011), may be more resilient to climatic shifts due to broader ecological tolerance (Blaha et al. 2006; Ruprecht et al. 2012; Wagner et al. 2020).

Diversity Patterns and Community Composition

Alpha diversity was highest at the lowest elevation (1168 m a.s.l.) for two out of three symbiotic partners, photobionts and microbiome. The mycobiont showed a non-linear response, with diversity lowest at the mid-elevation site (Hexenküche, 2153 m a.s.l.) and recovering at the highest site (Hochtor, 2562 m a.s.l.), whereas bacterial microbiome diversity decreased continuously with elevation. Differences in bacterial microbiome alpha diversity between sites were statistically significant. Photobiont diversity was particularly low at Hexenküche, where only a single OTU (*Tr_S02*) was recorded across all replicates. Given this single observation, no elevational trend can be inferred for photobiont diversity at this site. These divergent responses of the symbiotic partners to the elevational gradient are partly consistent with findings from Antarctic and Himalayan lichen communities (Wagner et al. 2021; Nanda et al. 2021).

Beta and gamma diversity analyses further revealed greater taxonomic turnover among mycobionts than photobionts, suggesting asymmetric diversity dynamics. This may reflect the higher richness of fungal partners and the tendency of some photobionts to associate with multiple hosts (Ruprecht et al. 2020; Wagner et al. 2021). Similar declines in beta diversity with increasing elevation have been documented in broader alpine studies (Nanda et al. 2021), indicating a shift in modular community composition along gradients.

The bacterial communities were dominated by members of the family *Acidobacteraceae*, followed by *Acetobacteraceae* and representatives of the order *Solibacterales*. All these taxa are commonly associated with acidic, oligotrophic environments. Microbiome composition varied considerably among replicates within the same site, suggesting that a substantial proportion of the bacterial community consists of sporadically occurring, unspecific taxa. However, the significant structuring of bacterial communities by mycobiont identity and, even more strongly, by photobiont OTU indicates that at least a subset of the bacterial taxa shows consistent associations with the major lichen symbionts. This is consistent with recent findings that symbiont identity is a key driver of microbial community structure in lichens (Grube et al. 2009; Schneider et al. 2011).

CAP analyses confirmed significant effects of elevation, mycobiont species identity, and photobiont OTU on bacterial microbiome composition, while overall community composition across sites did not differ significantly when all symbiotic partners were considered together. As shown in the CAP ordination (Fig. 4), bacterial assemblages clustered not only along elevation, but also according to dominant mycobiont taxa and photobiont lineages. These results indicate that lichen-associated bacterial communities are shaped jointly by environmental filtering and host-specific symbiotic configuration, rather than forming a uniform community independent of the host, in line with previous studies (Hodkinson et al. 2012; Aschenbrenner et al. 2014; Grube et al. 2015).

Photobiont Sharing and Network Flexibility

The ability of certain mycobionts, such as *Candelariella vitellina*, to associate with more than one photobiont simultaneously within a single thallus, as observed in sample 27 at Hochtor (Fig. 7) and consistent with findings in *Ramalina farinacea* (Casano et al. 2011), suggests the coexistence of multiple photobiont lineages rather than sequential photobiont

switching. These findings support hypotheses on photobiont flexibility as an adaptive strategy in changing environments (Blaha et al. 2006; Leavitt et al. 2013; Singh et al. 2017).

Photobiont sharing among mycobionts was a notable pattern. *Tr_S02*, in particular, was associated with a wide range of fungal taxa across sites, reinforcing the concept of local photobiont pools from which multiple mycobiont species recruit their photosynthetic partners (De Carolis et al. 2022; Peksa et al. 2022). This shared usage potentially enhances ecological robustness by enabling alternative symbiotic combinations under environmental stress (Duran-Nebreda & Valverde 2023).

Despite spatial proximity, microbiomes were unexpectedly heterogeneous, pointing to fine-scale environmental filtering and modular structuring of lichen communities. As proposed by Duran-Nebreda & Valverde (2023), submodular network architecture may facilitate adaptive reconfiguration of symbiotic associations, promoting resilience in dynamic alpine environments.

Conclusion

This study reveals distinct patterns of symbiotic diversity and interaction along a steep elevational gradient in an alpine environment. The highest alpha diversity occurred at lower elevations, particularly for mycobionts and the bacterial microbiome. In contrast, the photobiont *Tr_S02* was in most cases dominant in all habitats associated with almost all mycobionts which resulted in the lowest alpha diversity, suggesting that local symbiotic partner pools facilitate dynamic guild formation.

Microbiome composition was highly variable even at small spatial scales, reflecting the combined influence of symbiont identity, microhabitat conditions, and stochastic colonization processes. This highlights the complexity and modularity of lichen communities and their potential for adaptive flexibility.

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Competing Interests

The Authors declare no competing interests.

Author Contributions

Funding acquisition: UR, RRJ; Conceptualization MM, UR, RR; Formal Analyses MM, UR; Investigation MM, UR; Methodology MM, RRJ, UR; Resources UR, RRJ; Visualisation MM; Original Draft Preparation MM, UR; Review & Editing MM, UR, RRJ.

Data availability

Sequences were uploaded on the NCBI database, BioProject accession number PRJNA1364001, the complete dataset can be found in the supplementary information.

Electronic Supplement

https://www.zobodat.at/pdf/supp/Mittag_et_al_Supplement.pdf

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Mitteilungen aus der Gesellschaft – ZooBot-Jahresbericht 2025

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Vorwort

Die Arbeit an diesem Jahresbericht zeigte uns einmal mehr, wie vielfältig und erfreulich sich das vergangene Vereinsjahr der Zoologisch-Botanischen Gesellschaft in Österreich gestaltet hat. Vielleicht haben auch Sie an Veranstaltungen teilgenommen oder mitgewirkt und blicken gemeinsam mit uns gerne auf zahlreiche gelungene Aktivitäten zurück.

Trotz dieser positiven Entwicklung bleibt die finanzielle Situation der ZooBot angespannt. Um weiterhin ein hochwertiges und zugleich niederschwelliges Programm anbieten zu können, sind wir auf neue Mitglieder und Spenden angewiesen. Laufende Kosten für Publikationen, Organisation und Infrastruktur können durch Mitgliedsbeiträge allein nicht vollständig gedeckt werden. Gerade deswegen möchten wir uns besonders bei jenen bedanken, die im vergangenen Jahr die ZooBot mit einer Spende bedacht haben – insbesondere beim Team der Wildtierhilfe Wien rund um Evelyn Moser-Gattringer und Rebecca Fränzle für ihre großzügige Spende.

Wenn Sie Menschen kennen, die sich für eine Mitgliedschaft interessieren oder die ZooBot unterstützen wollen, empfehlen Sie uns gerne weiter. Dieser Jahresbericht gibt einen umfassenden Einblick in unsere Arbeit, die durch Mitgliedschaften maßgeblich unterstützt wird.

Wir wünschen Ihnen eine anregende Lektüre!

Das Vereinsjahr

Arbeit des ZooBot-Vorstandes und des Wissenschaftlichen Beirates

Im Zuge der Generalversammlung der ZooBot am 9. April 2025 (Mitglieder erhielten das Protokoll virtuell zugesandt) wurde insbesondere die finanzielle Situation der ZooBot diskutiert, denn jährlich schrumpfen die Reserven der ZooBot und beeinflussen die Zukunftsaussichten unseres Vereins stark. Die ZooBot als hochaktiver Verein mit 62 Veranstaltungen

im Jahre 2025 nebst anderen Angeboten, und trotz des hohen freiwilligen Einsatzes des Teams in der Freizeit – kann nicht ausschließlich ehrenamtlich geführt werden. So belasten insbesondere Personalkosten und Betriebsausgaben das Budget. Diese Entwicklung ist zwar keine neue, doch wurde sie erfreulicherweise bei der Generalversammlung von den anwesenden Mitgliedern aufgegriffen und thematisiert. Im Anschluss gründete Maximilian Petrasko, Kassier der ZooBot, eine „Task Force Finanzen“, um langfristig das Budget für Personal (Geschäftsführung und Redaktion der *Acta ZooBot Austria*) und damit das Angebot der ZooBot aufrecht zu erhalten. Die Arbeitsgruppen der Task Force Finanzen brauchen dringend Hilfe, und unsere Mitglieder, die sich an den Bemühungen für Sponsoring, Spendenakquise und andere Mittel beteiligen möchten, sind herzlich eingeladen mitzuhelfen! Die Zusammenarbeit in der Task Force Finanzen erfolgt online und ist damit von überall her möglich. Interessierte, bitte bei Maximilian Petrasko melden (Kontakt: maximilian.petrasko@univie.ac.at)!

Die Vorstandssitzungen, die seit Herbst 2025 vierteljährlich und damit regelmäßig virtuell stattfinden, hatten ebenfalls die Finanzen zum Schwerpunkt. Daneben befassten sich Vorstand und Wissenschaftlicher Beirat erneut mit vielen Themen rund um Förderung von Wissenschaft und Naturschutz, insbesondere auch Appelle und Offene Briefe an Stakeholder für Naturschutz und Förderung der Wissenschaft betreffend. Eine Liste entsprechender Themen und Vorstandsbeschlüsse findet sich in Tabelle 1. Besonders hervorzuheben sind der Offene Brief „Appell an die Steiermärkische Landesregierung betreffend Umweltschutz Steiermark“, für den die ZooBot aktiv Unterschriften im wissenschaftlichen Kollegium und unter Vereinen und Institutionen gesammelt hat und der deutliches Medienecho hervorrief (s. Tabelle 1, Beschluss vom 10.07.2025).

Da im Jahr 2025 keine Vorstandswahl stattfand, gab es nur kleinere Änderungen im Team der ZooBot (s. Appendix A).

Das Angebot für ZooBot-Mitglieder, sich Binokulare und Mikroskope kostenfrei auszuleihen, wurde ausgebaut: Mittlerweile sind diese an der Grünen Schule sowie bei der STV Biologie am UBB, Djerassiplatz, Wien platziert, um die Verfügbarkeit zu erhöhen. Jedes Mitglied kann sich die Geräte mehrere Wochen lang (Verfügbarkeit vorausgesetzt) kostenfrei ausleihen. Damit sollen insbesondere Studierende und Interessierte gefördert werden, beispielsweise bei der Einarbeitung in eine Artengruppe, für die Nutzung während eines Praktikums o.ä.. Mehr Informationen hierzu sowie das Formular zur Ausleihe finden sich auf der ZooBot-Homepage unter den Vorteilen für Mitglieder: <https://www.zoobot.org/mitgliedschaft/>

Die Initiative Öko-nnect wurde 2025 in einem virtuellen Treffen unterschiedlicher Vereine und Institutionen fortgesetzt. Dabei wurden verschiedene Themen rege diskutiert und einige Projekte angedacht. Ein gemeinsamer Mailverteiler wurde eingerichtet. Wir freuen uns auf eine baldige Fortsetzung der Initiative!

Tab. 1: Beschlüsse des Vorstandes der Zoologisch-Botanischen Gesellschaft in Österreich im Jahr 2025.

Datum	Inhalt
13.01.2025	Unterzeichnung “Offener Brief für zielorientierte Innovationen im nächsten Regierungsprogramm” inkl. eigenes Statement “Unterstützender Appell für innovative Biodiversitäts- und Umweltpolitik” Offener Brief: https://www.wu.ac.at/fileadmin/wu/d/i/ecocon/PDF/Offener_Brief_2025.pdf Statement: https://www.biodiversityaustria.at/wp-content/uploads/2025/01/20250114_OffenerBrief_Wissenschaft_der_Biodiversitaet_an_RegierungsverhandlerInnen_WEB.pdf
18.03.2025	Unterzeichnung eines vom Ö. Naturschutzbund Wien initiierten Offenen Briefes an Bürgermeister Ludwig zur Situation der Lobau https://naturschutzbund.at/neuigkeiten-liste-312/items/offener-brief-an-buergermeister-ludwig-zur-situation-der-lobau.html
15.05.2025	Unterstützung der GYBN-Stellungnahme der Jugend zu Renaturierung https://www.gybn-austria.at/2025/05/09/jugendstatement-renaturierung-in-osterreich/
06.05.2025	Unterzeichnung eines LOI für Projekt “Oceans Hub Austria” https://www.zoobot.org/wp-content/uploads/2026/02/20250506_Letter-of-Support_Ocean-Hub-Austria.pdf
10.07.2025	Unterzeichnung des Offenen Briefes “Appell an die Steiermärkische Landesregierung betreffend Umweltschutz Steiermark” + Unterschriftensammlung gemeinsam mit Dr. Karin Hochegger https://www.zoobot.org/wp-content/uploads/2025/08/Offener-Brief_Umweltschutz-Steiermark_2025_Komposch-Berg-Hochegger-Holzinger-Weiss.pdf
13.08.2025	Vorstandsbeschluss zur Unterstützung des Vereins Naturkundliche Gesellschaft Mostviertel: Überlegungen bzgl. Fortführung der “Freilandforscherkarte” durch die ZooBot
18.10.2025	3 Beschlüsse: a) Stellungnahme der ZooBot zum Gesetzesentwurf zum “Erneuerbaren-Ausbau-Beschleunigungsgesetz – EABG” https://www.parlament.gv.at/PtWeb/api/s3serv/file/612f161f-6a59-4804-be33-b430848e3bb9 b) Unterzeichnung des Offenen Briefes der ital. Region Ligurien (in Koordination mit WWF Italien) an Ursula von der Leyen, in dem für die Beibehaltung des LIFE-Programms plädiert wird https://efeverde.com/wp-content/uploads/2025/10/Joint-letter-LIFE-en.docx c) Unterstützung des Offenen Briefes “Climate Neutrality is Europe’s Greatest Economic Opportunity” https://zenodo.org/records/17399532
15.12.2025	Abstimmung zur Mitgliedsbeitragserhöhung, die der Generalversammlung 2026 vorgeschlagen werden soll

Aus der ZooBot-Redaktion

Band 161 der *Acta ZooBot Austria* erschien Ende 2025 mit dem Schwerpunkt-Thema „Biologie-Didaktik, Ökopädagogik und Wissenschaftsvermittlung“. Mit der Wahl dieses Themas unterstreicht die ZooBot ihr Selbstverständnis als Schnittstelle zwischen Universitäten und Schulen, zwischen wissenschaftlicher Forschung und elementarer Bildung. Ab diesem Band werden alle in der *Acta* veröffentlichten Beiträge mit einem Digital Object Identifier (DOI) versehen, was die Auffindbarkeit und Streuung der Arbeiten deutlich verbessert.

In der Redaktion hat es auch eine personelle Änderung gegeben. Rudolf Maier hat sich 2025 von seiner langjährigen Tätigkeit als Redakteur der *Acta* zurückgezogen. Seinem Engagement war das regelmäßige Erscheinen der *Acta* über viele Jahre hinweg maßgeblich zu verdanken. Wir danken ihm sehr für diesen Einsatz!

Aus der Bibliothek

Die Bibliothek der ZooBot wird kontinuierlich erweitert. Besonders der laufende Schriftentausch mit nationalen und internationalen Partnerinstitutionen trägt zum Bestandszuwachs bei. Im Berichtsjahr wurden rund 130 neue Zeitschriftenbände und Monografien in den Katalog aufgenommen. Die Zahl der Entlehnungen lag bei etwa 75.

Die im Zuge des Literaturumzugs 2021 erforderlich gewordene Neukatalogisierung der Monografien konnte mit Ende 2025/ Anfang 2026 vollständig abgeschlossen werden. Für die tatkräftige Unterstützung bei dieser umfangreichen Aufgabe danken wir erneut den ehrenamtlichen Mitarbeiterinnen Xena Mayer und Petra Hudler sehr herzlich.

Wie in jedem Jahr laden wir dazu ein, die reichen Bestände unserer Bibliothek zu nutzen. Die ZooBot-Bibliothek verbindet wertvolle historische Werke mit aktueller Fachliteratur und steht Wissenschaftler:innen aller biologischen Disziplinen ebenso offen wie allen, die sich für biologische Themen begeistern. Ein Besuch lohnt sich: Mit einer u:card oder einer ZooBot-Mitgliedschaft können Zeitschriften und Monografien entlehnt werden. Zudem steht ein Buchscanner zur Verfügung; bitte bringen Sie für dessen Nutzung wie gehabt einen eigenen USB-Stick mit.

Aus den Sektionen

Innerhalb der ZooBot haben sich zuletzt drei thematische Sektionen etabliert, die unterschiedliche Schwerpunkte setzen: Die **Sektion ProMare** widmet sich Fragen der Meeresforschung und des Meeresschutzes. Die **Sektion Geschichte der Biologie** beschäftigt sich mit verschiedenen Facetten der österreichischen Wissenschaftsgeschichte im Bereich der Biologie. Die **Sektion Junge ZooBot** legt ihren Fokus besonders auf die Förderung des wissenschaftlichen Nachwuchses.

Viele der laufenden Vorhaben sind mit erheblichem Engagement verbunden, weshalb Unterstützung jederzeit willkommen ist. Alle Mitglieder sind eingeladen, sich an bestehenden Projekten zu beteiligen oder eigene Ideen einzubringen, sei es eigenständig oder im Team, und so das Vereinsleben aktiv mitzugestalten. Auch Interessierte, die (noch) keine Mitglieder

sind, können gerne unverbindlich hineinschnuppern. Bei Interesse freuen sich die jeweiligen Sektionssprecher über eine Kontaktaufnahme per E-Mail.

ZooBot-Sektion ProMare – Jörg Ott: joerg.ott@univie.ac.at

ZooBot-Sektion Geschichte der Biologie – Friedrich Gusenleitner:
sektion.geschichte@zoobot.org

Junge ZooBot – Philipp Hummer: junge@zoobot.org

Nähere Informationen zu den Aktivitäten der einzelnen Sektionen finden Sie auf der ZooBot-Homepage.

ZooBot-Sektion Geschichte der Biologie

Auch 2025 entfaltete die Sektion Geschichte der ZooBot eine rege Tätigkeit mit unterschiedlichen Schwerpunkten.

Ein zentrales Arbeitsfeld blieb das Buchprojekt der Arbeitsgruppe „k.k. Zoologische Station Triest“. Unter der Koordination von Gerhard Aubrecht wird weiterhin an der Publikation „*Triest(e) – the Zoological Station in the Adriatic Sea (1875–1918). Early Contributions to Marine Biology*“ gearbeitet.

Darüber hinaus wurde für Sektionsmitglieder und weitere Interessierte eine Führung durch die Österreichische Mediathek in Wien organisiert.

Von großem Wert ist zudem die Expertise jener Mitglieder, die sich intensiv mit der Geschichte der ZooBot auseinandergesetzt haben. Sie unterstützen bei mittlerweile zahlreichen nationalen und internationalen Anfragen zu historischen Persönlichkeiten der Gesellschaft. Hervorzuheben ist dabei insbesondere Manfred Walzl, der die Geschichte der ZooBot wie nur wenige andere Personen kennt und hier regelmäßig Auskunft gibt.

ZooBot-Sektion ProMare

Einen wesentlichen Arbeitsschwerpunkt setzte das ProMare-Team im Berichtszeitraum wieder auf die Entwicklung des Projekts BlueList. Ziel dieser Initiative ist es, Personen in Österreich sichtbar zu machen, die sich – im weitesten Sinne – mit meereskundlichen Fragestellungen und dem Schutz der Meere beschäftigen. Über eine Online-Plattform sollen Expert:innen mit ihren Kontaktdaten und fachlichen Schwerpunkten auffindbar sein. Damit möchte BlueList den Austausch erleichtern, den Zugang zu Expertise zu Ozeanen und ihren Organismen verbessern sowie die Anbahnung von Kooperationen unterstützen.

Außerdem veröffentlichte die Sektion 2025 erneut zwei Artikel in den BlueNews, eine in den ZooBot-Newsletter integrierte Kategorie, die kurze Artikel über aktuelle Probleme der Ozeane enthält und über Arbeitsgruppen, Projekte und Publikationen im Bereich der Meereskunde in Österreich berichtet: So gab es einen Artikel von Mark Hartl über die Langzeitauswirkungen des Tiefseebergbaus und potenzielle Erholung abyssaler Gemeinschaften

sowie den Artikel von Paul Trautendorfer „*Munition im Meer: Wenn Meeresforschung auf Industrie und Sicherheitspolitik trifft*“.

Darüber hinaus beteiligte sich die Sektion erneut an der gemeinsamen Veranstaltungsreihe mit dem Verein „Haus des Meeres – Wissenschaft und Forschung (WiFo)“ und organisierte einen marinbiologischen Vortrag im Lighthouse¹⁰: Am 10. November 2025 referierte Nicolas Entrup (Ocean Care) zum Thema „*Tatort Mittelmeer – Wale und die Schifffahrt auf Kollisionskurs*“. Die Veranstaltung stieß auf großes Interesse und war sehr gut besucht.

ZooBot-Sektion Junge ZooBot

Die Arbeit der im Vorjahr gegründete Sektion „Junge ZooBot“ nahm 2025 an Fahrt auf. Insbesondere Exkursionen (s. Veranstaltungen) sowie die Bestimmungsabende zur Erweiterung der Artenkenntnis bildeten Schwerpunkte. Aus den Bestimmungsabenden heraus ergab sich außerdem das Projekt „*Die Tierwelt des Botanischen Gartens 2.0*“, in dem gemeinsam mit einer großen Zahl Freiwilliger – etablierte Wissenschaftler:innen und Studierende – eben jene erhoben wurde. Außerdem wurde die Mitarbeit in den naturhistorischen Sammlungen des Stiftes Seitenstetten fortgesetzt, wobei die Junge ZooBot den Kustos Mathias Weis (Wissenschaftlicher Beirat ZooBot) unterstützt – besonders schön ist, dass das Stift als Gründungsort der Sektion weiter einer ihrer Wirkungsorte bleibt. Auch eine studentische Feier anlässlich des Pensionsantritts für Harald Krenn (Wissenschaftlicher Beirat ZooBot) wurde durch die Junge ZooBot erfolgreich organisiert (s.u. Veranstaltungen).

Im Detail: Rückblick auf die Bestimmungsabende 2025

Jeden zweiten Mittwoch (um 18:30 Uhr im Seminarraum 1.7) finden am University of Vienna Biology Building (UBB, Djerassiplatz) zoologische Bestimmungsabende statt, bei denen sich Neulinge und erfahrenere Artenkenner:innen austauschen können. Dabei gibt es sowohl freie Bestimmungsabende, bei denen unterschiedliche Taxa bearbeitet werden, sowie Thementage, an denen geladene Expert:innen Vorträge zur Bestimmung von bestimmten Gruppen halten und ihre Erfahrung teilen.

Die Bestimmungsabende an der Universität Wien waren im Jahr 2025 von zahlreichen Kooperationen geprägt. Neben rund 20 offenen Terminen an der Universität Wien fanden auch vier Veranstaltungen im Naturhistorischen Museum statt, bei denen unterschiedliche Kurator:innen ihre Fachgruppen anhand von Museumsmaterial präsentierten. So wurden dort die Raubfliegen, Wildbienen, Ameisen und Schlupfwespen den vielen teilnehmenden Studierenden nähergebracht.

Auch bei den Terminen an der Universität Wien wurden immer wieder Expert:innen eingeladen, um ihre Tiergruppen vorzustellen und gemeinsam mit den Studierenden deren Bestimmung zu üben. Die Abende waren durchgehend gut besucht und sollen daher auch im Jahr 2026 fortgeführt werden.

Darüber hinaus waren die Bestimmungsabende im Februar 2025 im Rahmen der Tage der Biodiversität an der Universität für Bodenkultur vertreten, wo ein Workshop zum Bestimmen und Präparieren von Insekten angeboten wurde.



Abb. 1: Vortrag von Mario Oswald über die europäischen Gottesanbeterinnen am UBB Wien am 09.12.2025. (Foto: Elisabeth Glatzhofer) | **Fig. 1:** Talk by Mario Oswald on European praying mantises at the UBB Vienna on 9 December 2025. (Photo: Elisabeth Glatzhofer)

Abb. 2: Einführungsvortrag beim Bestimmungsworkshop der Wildbienen mit Sabine Schoder am Naturhistorischen Museum Wien am 11.03.2025 (Foto: Elisabeth Glatzhofer) | **Fig. 2:** Introductory talk at the wild bee identification workshop with Sabine Schoder at the Natural History Museum, Vienna, on 11 March 2025. (Photo: Elisabeth Glatzhofer)

Abb. 3: Eindruck aus dem Workshop bei den Tagen der Biodiversität an der Universität für Bodenkultur am 28.02.2025. (Foto: Tage der Biodiversität 2025, Christoph Gruber / BOKU University) | **Fig. 3:** A scene from the workshop at the Biodiversity Days at the University of Natural Resources and Life Sciences on 28 February 2025. (Photo: Biodiversity Days 2025, Christoph Gruber / BOKU University)

Außerdem entstand von den Bestimmungsabenden ausgehend ein Kooperationsprojekt mit dem Botanischen Garten der Universität Wien, bei dem die Fauna des Gartens von Expert:innen gemeinsam mit Studierenden systematisch erhoben wurde. Die Ergebnisse dieses Projekts sollen in einem kommenden Band der *Acta ZooBot Austria* veröffentlicht werden.

Veranstaltungen

Überblick

Insgesamt wurden im Jahr 2025 von und mit der ZooBot – zusätzlich zu den 24 Bestimmungsabenden – 38 weitere Veranstaltungen durchgeführt, die durchwegs großen Anklang fanden. Eine vollständige Übersicht findet sich in Appendix B. Da eine ausführliche Darstellung aller Termine den Rahmen dieses Jahresberichts sprengen würde, stellen wir im Folgenden exemplarisch einige ausgewählte Veranstaltungen vor. Sie stehen stellvertretend für das große Spektrum an Themen und Formaten, die unser Programm auszeichnen. Einen umfassenden Überblick bietet zudem der laufend aktualisierte Veranstaltungskalender sowie das Archiv auf unserer Homepage. Aktuelle Hinweise erhalten Mitglieder über die „ZooBot-News“, Interessierte ohne Mitgliedschaft können einen weniger ausführlichen, kostenlosen Newsletter im light-Format abonnieren.

Die Organisation dieser vielfältigen Angebote ist ein großer Bestandteil unserer Vereinsarbeit. Mit Vorträgen, Workshops, Exkursionen, Symposien und Stammtischen verfolgen wir konsequent unsere Ziele: die Förderung biologischer Forschung, die Stärkung des Naturschutzgedankens und die Vernetzung innerhalb der Fachcommunity. Gerade dieser Austausch ist uns ein besonderes Anliegen. Deshalb setzen wir bei der Planung unserer Veranstaltungen bevorzugt auf Kooperationen mit Partnerorganisationen. Die Zusammenarbeit mit Vereinen, Museen, Universitäten und weiteren Institutionen erleben wir als große Bereicherung – sie erweitert Perspektiven, schafft neue Kontakte und verteilt zugleich die organisatorische Verantwortung auf mehrere Schultern. Für diese engagierten und freundschaftlichen Kooperationen sind wir sehr dankbar.

Veranstaltungskalender: <https://www.zoobot.org/veranstaltungskalender/>

Veranstaltungsarchiv: <https://www.zoobot.org/veranstaltungsarchiv/>

Veranstaltungsnewsletter: <https://www.zoobot.org/newsletter/>

Einblicke in einige ZooBot-Veranstaltungen 2025

Tage der Biodiversität 2025

Die Tage der Biodiversität, die sich mittlerweile zur bedeutendsten Fach- und Stakeholderkonferenz der Biodiversität entwickelt haben, fand 2025 erneut an der BOKU University in Wien statt und zählte bemerkenswerte 500 Teilnehmer:innen aus dem In- und angrenzenden Ausland. Seit 2023 ist die ZooBot als Co-Organisator in die Tagung eingebunden, einerseits in der Organisation der Tagung selbst, andererseits konnten wir drei der vielen Parallelsessions (mit-)organisieren:

Die Vorbereitungen der Konferenz bildeten somit einen Schwerpunkt der Arbeit der ZooBot, in einem guten Team gemeinsam mit anderen Vereinen und Institutionen. Die Nachbereitungen sind für die ZooBot augenscheinlich erst mit der Veröffentlichung des vorliegenden *Acta ZooBot Austria*-Bandes abgeschlossen, der die Beiträge der Tage der Biodiversität als



Abb. 4: Elisabeth Kopp, Geschäftsführung der ZooBot, begrüßt die Teilnehmer:innen. (Foto: Tage der Biodiversität 2025, Christoph Gruber / BOKU University) | **Fig. 4:** Elisabeth Kopp, Managing Director of ZooBot, welcomes the participants. (Photo: Biodiversity Days 2025, Christoph Gruber / BOKU University)

Abb. 5: Die abschließende Podiumsdiskussion bei den Tagen der Biodiversität; ZooBot-Präsidentin Elisabeth Haring am Wort. (Foto: Tage der Biodiversität 2025, Christoph Gruber / BOKU University) | **Fig. 5:** The closing panel discussion at the Biodiversity Days; ZooBot President Elisabeth Haring speaking. (Photo: Biodiversity Days 2025, Christoph Gruber / BOKU University)

Themenschwerpunkt gesetzt hat – während wir uns bereits mit den Vorbereitungen für die Tage der Biodiversität 2027 in Innsbruck beschäftigen.

Das ZooBot-Team, in diesem Fall bestehend aus Elisabeth Haring, Helmut Sattmann, Andreas Tribsch, Matthias Kropf und Elisabeth Kopp, organisierte eine eigene Session zum Thema „*Defizite der taxonomischen Forschung in Österreich*“, die mit rund 100 Teilnehmer:innen erfreulich gut besucht war. Die Förderung der Taxonomie ist eines unserer erklärten Ziele und liegt – offensichtlich nicht alleine – der ZooBot sehr am Herzen.

Außerdem veranstaltete die Gruppe „Bestimmungsabende“ der Jungen ZooBot einen ganz praktischen Workshop (s. auch oben, Sektion Junge ZooBot):

Verschiedenes Insekten-Material wurde bereitgestellt, an dem jede:r, mit Support durch die Biolog:innen, Insektenbestimmung und Bestimmungsschlüssel ausprobieren durfte. Der Workshop war so gestaltet, dass Teilnehmer:innen spontan länger oder auch nur kurz vorbeischaun konnten, dutzende Personen nahmen dieses Angebot wahr. Die Junge ZooBot nutzte die Gelegenheit der Tagung, sich der Öffentlichkeit als Sektion der ZooBot vorzustellen. Dieser Workshop wurde organisiert von Elisabeth Glatzhofer, Mario Oswald, Samuel Messner, Sebastian Ploner, Paul Röttger, Tobias Geiler und Elisabeth Kopp.

Außerdem brachte sich die ZooBot auch wieder in die Verleihung des NOBIS-Young-Researcher-Preises ein und stellte einen Teil des Preisgeldes – ebenfalls entsprechend dem Streben der ZooBot, gezielt Nachwuchs-Wissenschaftler:innen zu fördern.

Insgesamt waren die Tage der Biodiversität 2025 die bisher größte Biodiversitäts-Tagung in Österreich und eine starke Stimme für die Biodiversität. In der Zusammenarbeit liegt die Kraft, und um diese Aufgabe zu stemmen, stießen für diese Tagung weitere Partner zum Organisationsteam – die organisierenden Institutionen und Vereine waren 2025: Biodiversität-Hub, BOKU University, ABOL, NHM Wien, NOBIS, Universität Wien, Universität für Weiterbildung Krems.

Aufzeichnungen der Keynote-Vorträge 2025 finden sich zur Nachschau auf dem YouTube-Kanal der BOKU University: <https://www.youtube.com/@bokuwien>

Fotos, Abstractband und Tagungsprogramm 2025 finden sich auf der Tagungshomepage: <https://biodiversitaetstage.boku.ac.at/medien25/>

Lehrveranstaltungen/ZooBot-Hybrid-Vortragsreihen 2025

Im Jahr 2025 wurden in beiden Semestern erneut Hybrid-Vortragsreihen der ZooBot durchgeführt, die zugleich als Lehrveranstaltungen an der Universität Wien angeboten wurden. Studierende konnten die Reihen inskribieren und bei erfolgreichem Abschluss ECTS-Punkte erwerben. Darüber hinaus standen sämtliche Vorträge auch der interessierten Öffentlichkeit offen, sowohl vor Ort als auch online. Der niederschwellige Zugang zu wissenschaftlichen Themen und zum Naturschutz ist der ZooBot bekanntlich ein wichtiges Anliegen.

Inhaltlich widmete sich jedes Semester einem eigenen Schwerpunkt. Im Sommersemester 2025 wurde die bereits im vorigen Semester gestartete Reihe „*Unterschiedliche Fragen – unterschiedliche Herangehensweisen: Methodische Vielfalt in biologischer Forschung*“ fortgesetzt. Die große Bandbreite innovativer Methoden in der taxonomisch-organismischen Forschung wie auch im Naturschutz hatte ein einzelnes Semester nicht ausreichend abdecken können. Ebenfalls auf bemerkenswert großes Interesse stieß die Reihe „*Wissenschaft und Naturschutz – im Spannungsfeld zwischen Grundlagenforschung und Gesellschaft*“. Teilweise verfolgten über 100 Personen die Vorträge vor Ort und online. Die Beiträge spannten einen Bogen von Forschung und Aktivismus über Bahnökologie und alpine Floren im Klimawandel bis hin zu kontrovers diskutierten Fragen wie den ökologischen Auswirkungen der Wasserkraft und die Rolle neuer Staudämme in der Energiewende. Gerade das Zusammenspiel von Wissenschaft, Naturschutz und gesellschaftlichen Interessen erwies sich als besonders diskussionsreich. Die offene Atmosphäre, Vorträge auf Augenhöhe und intensive Debatten im Anschluss prägten die Veranstaltungen ebenso wie das vielfältige Publikum aus Studierenden, Wissenschaftler:innen, Interessierten und Vertreter:innen unterschiedlicher Stakeholder-Gruppen.

Ein herzlicher Dank gilt Mihaela Pavlicev, die die Lehrveranstaltung gemeinsam mit Christian Griebler bis einschließlich Sommersemester 2025 leitete und organisierte. Christian Griebler führt dankenswerterweise die Leitung weiterhin fort; seit dem Wintersemester 2025 verstärkt zudem ZooBot-Präsidentin Elisabeth Haring das Leitungsteam und trägt inhaltlich und organisatorisch unterstützt von Elisabeth Kopp zum Gelingen der Reihe bei.

Viele der Vorträge aus den Hybrid-Vortragsreihen konnten aufgezeichnet werden und stehen der Allgemeinheit auf dem YouTube-Kanal der ZooBot zur Nachschau zur Verfügung: <https://www.youtube.com/@zoobot>

Kooperationsveranstaltungen mit dem Verein „Haus des Meeres – Wissenschaft und Forschung“ (WiFo)

Auch im Jahr 2025 wurde die erfolgreiche Kooperation mit dem Verein „Haus des Meeres – WiFo“ unter ihrem neuen Präsidenten Michael Stachowich weitergeführt. Veranstaltungsort war erneut das „Lighthouse¹⁰“, der Vortragssaal im 10. Stock des Hauses des Meeres, der mit seinem beeindruckenden Blick über Wien einen besonderen Rahmen bietet.

Das Programm umfasste wieder insgesamt fünf Termine: zwei Thementage mit mehreren Fachvorträgen zu einem übergeordneten Schwerpunkt (begleitet von einem festlichen Ambiente, Getränken und teilweise auch mit Live-Musik) sowie drei eigenständige Abendvorträge in ausführlicherem Format (Titel siehe Appendix B). Sämtliche Veranstaltungen stießen auf großes Interesse und waren durchwegs sehr gut besucht.

Junge ZooBot: Exkursionen zur Erweiterung der Artenkenntnis: Verschiebebahnhof Breitenlee & Nationalpark Neusiedler See – Seewinkel

Die Junge ZooBot organisierte 2025 zwei Exkursionen zur Förderung von Arten- und Lebensraumkenntnis des wissenschaftlichen Nachwuchses, bei denen Interessierte herzlich willkommen waren:



Abb. 6: Seewinkel-Exkursion der Jungen ZooBot. (Foto: Paul Röttger) | **Fig. 6:** Seewinkel field trip organised by the Young ZooBot group. (Photo: Paul Röttger)

Vom Menschen aufgegebene Bauprojekte wie der Verschiebebahnhof Breitenlee entwickeln sich häufig zu echten Hotspots der Artenvielfalt – auch in der Großstadt. Der Verschiebebahnhof Breitenlee im 22. Wiener Gemeindebezirk hat sich zu einem bemerkenswerten Trockenrasen entwickelt, auf dem für Wien einzigartige Pflanzen und Tagfalter vorkommen. Tagfalter-Experte Harald Krenn machte sich gemeinsam mit der Gruppe am 14.06.25 auf die Suche nach den Tagfaltern der Fläche und vermittelte Bestimmung der dort häufigsten Arten. Für Interessierte gab es auch eine Einführung in das Citizen Science-Projekt „Tagfaltermonitoring eBMS“ der Austrian Butterfly Conservation (ABC).

Am 11. Oktober 2025 fand die zweite Exkursion der Jungen ZooBot statt. Diesmal ging es zum Nationalpark Neusiedler See-Seewinkel; die Exkursion war als „Schwarmwissen-Exkursion“ angelegt, wobei alle Teilnehmer:innen eingeladen waren, ihr Wissen beizutragen. Durch das Gebiet begleitete die Gruppe ZooBot-Geschäftsführung Elisabeth „Lilly“ Kopp. Neben der Bestimmung von allerlei Insekten, Vögel und Flora, machte sich die Gruppe mit den Lebensräumen der beweideten Halbtrockenrasen und der Sodalacken sowie der Naturgeschichte der Region vertraut. Besonders faszinierte das Mikrohabitat an den Sodalacken, wo bereits wenige Zentimeter Höhenunterschied zu einem unterschiedlichen Bewuchs führen können. Lilly teilte spannende Details zu aktuellen Tätigkeitsgebieten des Nationalpark. Mit dem Wetter hatte die Gruppe seewinkel-typisch dabei durchgehend großes Glück und konnte über den Tag verteilt eine Vielzahl seltener Vogelarten erspähen.

Junge ZooBot: Abschiedsfeier Harald Krenn

Harald Krenn war, unter anderem durch seine langjährige und ausgezeichnete Lehre, für viele Biolog:innen prägend – als Professor und durch sein breites außer-universitäres Engagement legendär. Seit seiner Pensionierung im Winter 2024 gab es dementsprechend auch einige Abschiedsfeiern in seinen unterschiedlichen Kreisen. Für die Studierenden der Jungen ZooBot war aber immer klar, dass es auch eine Abschiedsfeier von studentischer Seite geben müsse. Am 3.12.2025 war es dann schließlich nach Haralds endgültig letzter Vorlesung so weit: Im Anschluss an einen Vortrag von Thomas Wrba im ZooBot-Seminar zum Thema ökologische Restauration durch Beweidung gab es eine Überraschungsfeier. Diese begann

mit einer Laudatio von Csilla Tragner, welche für die Planung dieses Abends gemeinsam mit Simon Maynollo und Martina Darwich federführend war. Als Worldcafé angelegt, gab es Speis und Trank und es wurden Stationen aufgebaut, die Harald Krenns Lehre spielerisch nachempfanden. So gab es zum Beispiel ein Tier-Memory, man hatte Gelegenheit sich im Detail mit der Morphologie von (Origami-) Insekten auseinanderzusetzen und es gab Kostproben von Chilis und anderen scharfen Lebensmitteln (angelehnt an Harald Krenns berühmte erste Vorlesung in der StEOP 1). Wir bedanken uns recht herzlich bei allen Beteiligten und Gästen für diesen unvergesslichen Abend sowie ein weiteres Mal bei Harald Krenn für sein langjähriges Engagement und seinen unermüdlichen Einsatz für die Studierenden!

In Memoriam

„Mit jedem Menschen verschwindet ein Geheimnis aus der Welt,
das vermöge seiner besonderen Konstruktion nur er entdecken konnte,
und das nach ihm niemand wieder entdecken wird.“
– Friedrich Hebbel

Als wissenschaftliche Gesellschaft mit einer besonders langen Geschichte begleiten manche Mitglieder die ZooBot fast ihr Leben lang. Ihr Tod lässt uns mit Gedenken, Erinnerungen und Dankbarkeit für jahrzehntelange Zugehörigkeit zurück. Im Jahr 2025 verließ uns O. Univ.Prof.i.R. Dr. Erwin Führer, der bemerkenswerte 67 Jahre lang Mitglied der ZooBot war – in anderen Worten seit seiner Studentenzeit im Alter von 22 Jahren. Wir sprechen seiner Familie, seinen Freund:innen und Kolleg:innen unser tief empfundenes Beileid für ihren Verlust aus.

Erwin Führer

12.11.1936 – 01.12.2025

Jahrzehntelanges, auch unterstützendes Mitglied der ZooBot

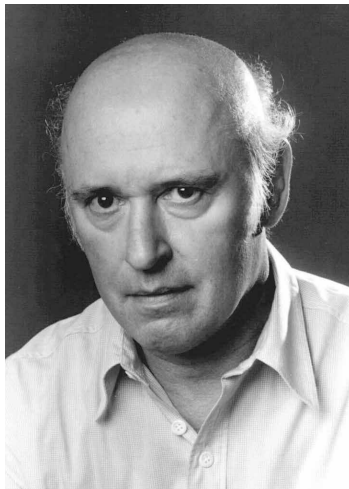


Abb. 7: Erwin Führer (Foto: ZOBO-DAT) | **Fig. 7:** Erwin Führer

Danksagung

Die Zoologisch-Botanische Gesellschaft zeichnet sich durch ihre thematische Vielfalt und das Engagement zahlreicher Mitwirkender aus. Viele Personen bringen sich ehrenamtlich und in ihrer Freizeit in Projekte, Veranstaltungen und organisatorische Aufgaben ein. Ein erheblicher Teil der Arbeit geschieht dabei im Hintergrund: Geschäftsführung, Vorstand, und Wissenschaftlicher Beirat widmen viele Stunden der Planung von Veranstaltungen, der Betreuung der Bibliothek sowie dem Erhalt unserer Infrastruktur (z. B. der Homepage).

Unser herzlicher Dank gilt daher allen Engagierten: dem Wissenschaftlichen Beirat, den Leiter:innen unserer Lehrveranstaltungen, den Referent:innen, den ehrenamtlichen Mitarbeiter:innen der Bibliothek, unseren Kooperationspartner:innen sowie den Autor:innen unserer Publikationen.

Ein besonderer Dank gebührt Ihnen, liebe Mitglieder. Mit Ihren Beiträgen, Spenden und Ihrer aktiven Teilnahme ermöglichen Sie unsere Arbeit und erfüllen unsere Veranstaltungen mit Leben. Bitte empfehlen Sie die ZooBot weiter, damit sie auch in Zukunft wachsen und gedeihen kann.

Wir freuen uns auf ein baldiges Wiedersehen, ob online, bei einer Veranstaltung oder im persönlichen Austausch.

Appendix

A: Team der ZooBot 2025

Vorstand

Präsidentin	Priv.-Doz. ⁱⁿ Mag. ^a Dr. ⁱⁿ Elisabeth Haring
Vizepräsidenten	Univ.Prof. Dr. Michael Kiehn Univ.Prof. Mag. Dr. Christian Sturmbauer
Schriftführer	Paul Röttger, MSc
Stv. Schriftführer	Assoz.Prof. Mag. Dr. Andreas Tribsch
Rechnungsführer	Maximilian Petrasko, BSc
Stv. Rechnungsführer	Assoz.Prof. ⁱⁿ DI ⁱⁿ Dr. ⁱⁿ Ursula Nopp-Mayr
Referenten Redaktion	Hofrat Dr. Helmut Sattmann
Vorstandsmitglieder ohne Funktion	Hofrat Dr. Gerhard Aubrecht ao. Univ.-Prof. Mag. Dr. Irmgard Greilhuber Hofrat Mag. Friedrich Gusenleitner Philipp Hummer, MSc Univ.Prof. Mag. Dr. Gabriel Singer

Wissenschaftlicher Beirat

Univ.Prof. Dr. Stefan Dötterl
Mag. Dr. Anton Drescher
Assoz.Prof. Mag. Dr. Franz Essl
Dr.ⁱⁿ Barbara-Amina Gereben-Krenn
Univ.Prof. i.R. Dr. Michael Götzinger
ao. Univ.Prof.ⁱⁿ Mag.^a Dr.ⁱⁿ Irmgard Greilhuber
Univ.Prof. Mag. Dr. Christian Griebler
Univ.Prof. i.R. Dr. Alois Herzig
Dr. Stefan Kapeller
Mag. Dr. Christian Komposch
Univ.Prof. Mag. Dr. Harald Krenn
Priv.Do. Dr. Matthias Kropf
Dr. Robert Lindner
Univ.Prof.ⁱⁿ Dr.ⁱⁿ Andrea Möller
Mag. Dr. Johann Neumayer
Univ.Prof. i.R. Dr. Jörg Ott
Univ.Prof. i.R. Dr. Hannes Paulus
Univ.Prof.ⁱⁿ Dr.ⁱⁿ Birgit Schlick-Steiner
Dr. Michael Stachowitsch
Mag.^a Ruth Swoboda
Univ.Prof. i.R. Dr. Roman Türk
Univ.Prof. i.R. Dr. Manfred Walzl
Laura Waldner MSc
Univ.Prof. Dr. Andreas Wanninger
Mag. Mathias Weis
Mag. Dr. Helmut Zwander

Rechnungsprüfer:innen

Priv.-Doz. Dr. Alexander Franz
Mag.^a Ursula Fraunschiel

Redaktions-Mitarbeiter

Mag. Benjamin Seaman

Geschäftsführung

Elisabeth Kopp, MSc

B: Veranstaltungen der ZooBot 2025

Datum	Veranstaltung
08.01.2025	Hybrid-Vortrag von Alon Mekinulov: <i>„Fotografie: von A wie Ethik bis Z wie Scicom“</i> *
14.01.2025	Exkursion: <i>„Führung durch die Österreichische Mediathek: Archiv der Vergangenheit und Gegenwart für die Zukunft“</i>
15.01.2025	Hybrid-Vortrag von Martin Kapun: <i>„Bioinformatik in der Evolutionsbiologie – und Evolution der Bioinformatik“</i> *
22.01.2025	Virtueller Vortrag von Andreas Tribisch: <i>„DNA-Barcoding & Metabarcoding bei Pflanzen in Forschung und Biodiversitätsschutz: was schon geht, bald gehen wird und wo die Grenzen der Anwendung liegen“</i> *
01.–02.02.2025	Botanische Illustrationen im Botanischen Garten – Kurs 1 – Bleistift
25.–28.02.2025	Tage der Biodiversität 2025
05.03.2025	Hybrid-Vortrag von Nesrine Akkari: <i>“Towards an integrative approach to collection-based systematics: examples from research on Myriapoda (Arthropoda) in the Natural History Museum Vienna”</i> **
19.03.2025	Hybrid-Vortrag von Monika Bright: <i>“The Underworld of Deep-Sea Hydrothermal Vents”</i> **
22.–23.03.2025	Botanische Illustrationen im Botanischen Garten – Kurs 2 – Tusche
09.04.2025	Hybrid-Vortrag von Christian Griebler: <i>„Methoden zur Erforschung unterirdischer Lebensräume“</i> **
09.04.2025	Wiener ZooBot-Stammtisch im Heurigen Zur Alten Weinpresse
26.– 27.04.2025	Botanische Illustration im Botanischen Garten – Kurs 3 – klassische botanische Illustration
28.04.2025	Vortragsabend <i>„Ökosystem Marchfeldkanal“</i> im Haus des Meeres (Referenten: Wolfgang Neudorfer, Günther Unfer, Franz Steiner), gemeinsam mit HdM-WiFo
07.05.2025	Hybrid-Vortrag von Ludwig Huber: <i>„Das rationale Tier – eine kognitionsbiologische Spurensuche“</i> **
12.05.2025	Schnecken-Exkursion im Miniaturformat: Schnecken-Erhebung der MoFa & ZooBot mit Hilfe von Freiwilligen im Zuge des Forschungsprojekts <i>„Die Tierwelt des Botanischen Gartens 2.0“</i> der Jungen ZooBot
21.05.2025	Virtueller Vortrag von Christian Komposch: <i>„Baumfallen, Alpine Klettertechnik und Astproben aus 45 m Höhe – Erste Einblicke in die Baumkronenfauna heimischer Wälder“</i> **
14.06.2025	Exkursion der Jungen ZooBot: <i>„Juwele der Industrie-Brache: Tagfalter auf der Stadtwildnis-Fläche Verschiebebahnhof Breitenlee“</i> ; Referent: Harald Krenn, gemeinsam mit Austrian Butterfly Conservation (ABC)

Datum	Veranstaltung
18.06.2025	Hybrid-Vortrag von Richard Zink „ <i>Angewandter Vogelschutz – Habitatmanagement, Monitoring & Wiederansiedlung</i> “***
18.06.2025	Wiener ZooBot-Stammtisch im Heurigen Zur Alten Weinpresse
19.09.2025	Mollusken-Exkursion auf den Anninger (Mödling, NÖ), gemeinsam mit Molluskenforschung Austria (MoFA)
20.09.2025	Pflegeeinsatz mit Exkursion und Jause am Zeiserlberg (NÖ), gemeinsam mit eNu und der Gemeinde Ottenthal
20.– 21.09.2025	Kurs: Botanische Illustration im Botanischen Garten
04.– 05.10.2025	Kurs: Botanische Illustration im Botanischen Garten
08.10.2025	Hybrid-Vortrag von Ulrich Eichelmann „ <i>Wissenschaftler:innen für die Natur – zwischen Forschung und Aktivismus</i> “; Vorstellung der ZooBot zu Semesterstart durch Elisabeth Haring und Elisabeth Kopp ***
11.10.2025	Exkursion der Jungen ZooBot mit Elisabeth Kopp im Nationalpark Neusiedler See-Seewinkel
13.10.2025	<i>Pilze: Leben in Bier, Mist und Meer</i> (Themenabend im Haus des Meeres); gemeinsam mit HdM-WiFo
20.10.2025	Vortrag im Haus des Meeres von Alessandro De Maddalena: „ <i>Great White Sharks of South Australia & the Mediterranean</i> “; gemeinsam mit HdM-WiFo
22.10.2025	Hybrid-Vortrag von Walter Traunspurger „ <i>Fadenwürmer – fade Würmer? Bedeutung der Fadenwürmer in unseren Gewässern</i> “***
05.11.2025	Hybrid-Vortrag von Steven Weiss „ <i>Auswirkungen der Wasserkraft auf Ökosysteme und die abnehmende Bedeutung neuer Staudämme für die Energiewende</i> “***
10.11.2025	Vortrag im Haus des Meeres von Nicolas Entrup: „ <i>Tatort Mittelmeer – Wale und die Schifffahrt auf Kollisionskurs</i> “; gemeinsam mit HdM-WiFo
19.11.2025	Hybrid-Vortrag von Harald Pauli „ <i>Alpine Gipfelhabitate und ihre Pflanzenarten im rapiden anthropogenen Temperaturanstieg</i> “***
19.11.2025	Vortrag von Christian Sturmbauer „ <i>Die Zoologisch-Botanische Gesellschaft in Österreich und ihre Relevanz für Studierende der Biologie</i> “ im Rahmen des Biologie-Kolloquiums an der Universität Graz
21.– 23.11.2025	Phylogenetisches Symposium: 100 years of Rupert Riedl: Systems Conditions for Evolution; Symposium der Universität Wien, ZooBot als Co-Sponsor
25.11.2025	Hybrid-Symposium: 8. <i>Workshop Österreichische Tropenforschung – Symposium „Wissenschaft an der Tropenstation La Gamba“</i> ; Kooperationsveranstaltung La Gamba Tropenstation & ZooBot
01.12.2025	Vortrag im Haus des Meeres von Michael Kiehn: „ <i>Botanische Gärten – Vergangenheit, Gegenwart und Zukunft</i> “; gemeinsam mit HdM-WiFo

Datum	Veranstaltung
03.12.2025	Hybrid-Vortrag von Thomas Wrбка „ <i>Nicht (nur) für Vegetarier – ökologische Restoration von Pastorallandschaften durch Beweidung am Beispiel des NP Neusiedler See-Seewinkel</i> “ ***
03.12.2025	Junge ZooBot: Studentische Abschiedsfeier für Harald Krenn, organisiert von Csilla Tragner, Simon Maynollo und Martina Darwich
17.12.2025	Hybrid-Vortrag von Thomas Schuh „ <i>Ökologie auf Schiene?! – Bahnökologie als neues Fachgebiet mit großer Zukunft</i> “ ***

* ZooBot-Vortrag im Rahmen der Lehrveranstaltung „Methodische Vielfalt in biologischer Forschung – Teil I“

** ZooBot-Vortrag im Rahmen der Lehrveranstaltung „Methodische Vielfalt in biologischer Forschung – Teil II“

*** ZooBot-Vortrag im Rahmen der Lehrveranstaltung „Wissenschaft und Naturschutz – im Spannungsfeld zwischen Grundlagenforschung und Gesellschaft“