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UNCERTAINTY AND QUALITY OF SPATIAL DATA IN ENVIRONMENTAL ANALYSES: FROM VISUALIZATION TO DECISION-MAKING

Habilitation thesis

Geoinformatics and cartography

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DECLARATION OF AUTHORSHIP

I declare that I have prepared the submitted habilitation thesis independently using properly cited literary sources.

Olomouc
September 16, 2025 Jan Brus

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AI USAGE DECLARATION

During the preparation of this habilitation thesis, several generative AI tools (ChatGPT 5, Google Gemini 2.5 Pro, Claude Sonnet 4, Claude Opus 4.1) were employed as language aids. Their application was limited to translation between Czech and English, language polishing, and maintaining stylistic consistency across the manuscript. These tools also supported the analysis and summarization of literature, literature search, and organization of references. The DeepL translator was used for additional verification of translations. All intellectual content presented in this work, encompassing the theoretical framework, research design, data analyses, and scientific conclusions, is entirely the author's own. Consequently, the author bears sole and full responsibility for the scientific integrity, accuracy, and interpretations contained within this thesis.

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LIST OF ABBREVIATIONS

AI	Artificial Intelligence.
COLOSS	*Prevention of honey bee COlony LOSSes* is an international, non-profit association headquartered in Bern, Switzerland that is focused on improving the well-being of honeybees at a global level
CWRs	Crop Wild Relatives
GeoAI	Geoinformatics Artificial Intelligence; integration of geoinformatics and artificial intelligence methods
GBIF	Global Biodiversity Information Facility
ISO	International Organization for Standardization
LGM	Last Glacial Maximum
Maxent	Maximum Entropy Model; software for modeling species habitat suitability
MOSPREMA	Project focused on monitoring and prediction of calamity mosquito outbreaks in Litovelské Pomoraví, Czechia
OGC	Open Geospatial Consortium
PLA	Protected Landscape Area
PSUP	Project Service of Palacký University in Olomouc
RQ	Research Question; used to denote the main research questions of the thesis (RQ1–RQ4)
VGI	Volunteered Geographic Information

MOTIVATION

We live in an era of rapid technological change where our decisions depend on **quality data** more than ever before. Information surrounds us, yet we typically use only a fraction of what is available. We have reached a point where 21st-century environmental and societal challenges—from climate change through invasive species management to landscape development require decisions based on increasingly complex spatial data.

In this dynamic period of change, geoinformatics has become a key discipline providing tools for collecting, analyzing, and visualizing these data. Approximately 0.4 zettabytes of data are produced daily, with a large portion being spatial (Statista, 2024). Data volume and heterogeneity continue to grow, encompassing expert interpretations, remote sensing data, and massive public participation through citizen science. With this growth, however, a fundamental yet often underestimated phenomenon emerges: **uncertainty**.

Uncertainty in the scientific sense has accompanied the author since writing bachelor's and master's theses, though it received little attention then. A fundamental shift occurred during Ph.D. studies when uncertainty visualization became the author's central scientific focus. The connection with environmental studies proved logical, given my previous educational background and emerging collaborations with colleagues from various departments. Uncertainty was inherent in most analyses, modeling, and map production in which the author participated. Through the author's involvement, what was an overlooked aspect became a fundamental problem worth further scientific development.

In the 12 years since completing the dissertation, approaches to uncertainty have not fundamentally changed. Historically, uncertainty in geoinformatics was understood primarily at the technical level as error or imprecision to be minimized and quantified. As discussed in the literature review, this view gradually expanded to include cognitive, communicative, and social aspects. The field has many partial methods for measuring, visualizing, and communicating uncertainty. However, a comprehensive and systematic framework connecting technical, cognitive, and application dimensions into a functional whole is still missing. Work with uncertainty is thus often understood as a partial technical problem rather than a complex communication challenge centered on the end user.

The aim of this habilitation thesis is **to develop and validate a user-centered approach for working with uncertainty and quality of spatial data in environmental analyses**. This approach connects theoretical conceptualization of uncertainty (RQ1), its identification and methodological treatment in heterogeneous data sources (RQ2), design and empirical validation of uncertainty visualization methods (RQ3), and application of uncertainty work in practical decision support tools (RQ4). The common denominator across all parts is the effort to **transform uncertainty from a barrier preventing effective data use into clearly communicated information** that enhances the quality of scientific conclusions and practical decision-making processes.

The habilitation thesis is built on **four main research questions**:

RQ1: How can uncertainty in environmental data be conceptualized from a user-centered perspective?

→ Addressed in **Chapter 2**, which delineates the theoretical concept and presents the fundamental philosophy of work.

RQ2: What are the sources of uncertainty and data quality in different types of heterogeneous data and how can they be methodologically addressed?

→ Addressed in **Chapter 3**, which demonstrates different uncertainty scenarios through three examples (expert interpretation, citizen science, interdisciplinary integration).

RQ3: How can we design and validate visualization methods that effectively communicate uncertainty and data quality to end users?

→ Addressed in **Chapter 4**, which has two complementary pillars: practical application in biogeography (4.1) and systematic empirical validation through user experiments (4.2).

RQ4: How can systematic work with uncertainty and data quality contribute to creating practical tools and supporting decision-making in environmental and societal contexts?

→ Addressed in **Chapter 5**, which synthesizes theoretical insights and application examples, demonstrating the practical impact of the proposed approach.

The thesis is thus not merely a compilation of the author's published works but presents a **comprehensive methodological approach across the entire chain**—from theoretical conceptualization through analysis and visualization to final impact.

The research questions are addressed through a structured analysis of eleven peer-reviewed publications integrated across Chapters 2–5 (**Figure 1**). Rather than presenting individual papers in isolation, each chapter synthesizes relevant publications to build a coherent argument: Chapter 2 establishes the theoretical framework, Chapter 3 demonstrates methodological approaches to different uncertainty sources, Chapter 4 validates visualization techniques, and Chapter 5 showcases real-world applications. This structure ensures that the theoretical premises articulated in this introduction are systematically developed into concrete scientific contributions.

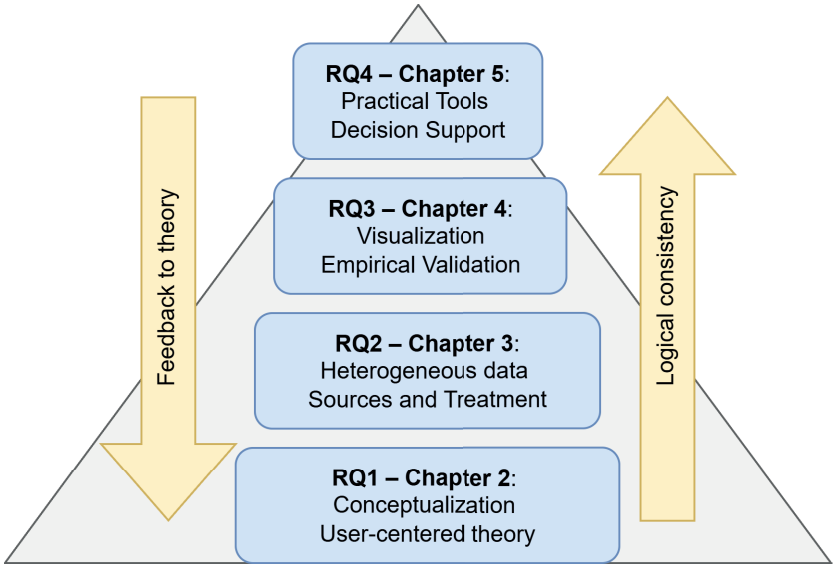


Figure 1: Logical structure of the habilitation thesis linking research questions (RQ1–RQ4) with chapters

Historical Development of Technical Concepts

The issue of working with **uncertainty and data quality** has a long history in geoinformatics and environmental sciences, and in environmental applications, it is further amplified by the higher spatial and temporal variability of studied phenomena, the need to combine heterogeneous data sources, and the requirement to communicate results to a broad spectrum of users, from experts to the public. These factors make working with uncertainty more domain-specific and demanding than in fields with more homogeneous data and standardized processes. The development in environmental applications thus reflects a shift from purely technical understanding of data quality to broader, user-oriented, and predominantly application-oriented frameworks. This development can be traced through the author's own studies. In the initial phase, the author's research focused primarily on clarifying and formalizing the very concept of uncertainty and data quality, while later work placed greater emphasis on user and application aspects. Looking back historically, in the 1980s and 1990s (**Figure 2**), a purely technical view prevailed. Uncertainty was then identified primarily with error, and positional accuracy was the most important monitored parameter. Research at that time focused on quantifying these errors and tracking their propagation in spatial analyses. Goodchild (Goodchild, 2009) emphasized the need to precisely define basic dimensions of uncertainty and work with them systematically. Veregin (Veregin, 1995) pointed out that even small errors can significantly distort results through accumulation in more complex models. These approaches were subsequently applied in many areas, from assessing digital terrain model accuracy, remote sensing image classification, to hydrological modeling. Simultaneously, data quality frameworks began forming that evaluated not only accuracy but also considered other parameters (Devillers et al., 2006). The gradual revelation and quantification of errors became the foundation for systematic data quality frameworks. Once it was clear that uncertainty could not be reduced only to positional accuracy, the need arose for unified norms and standards that would further describe **various dimensions of spatial data quality**.

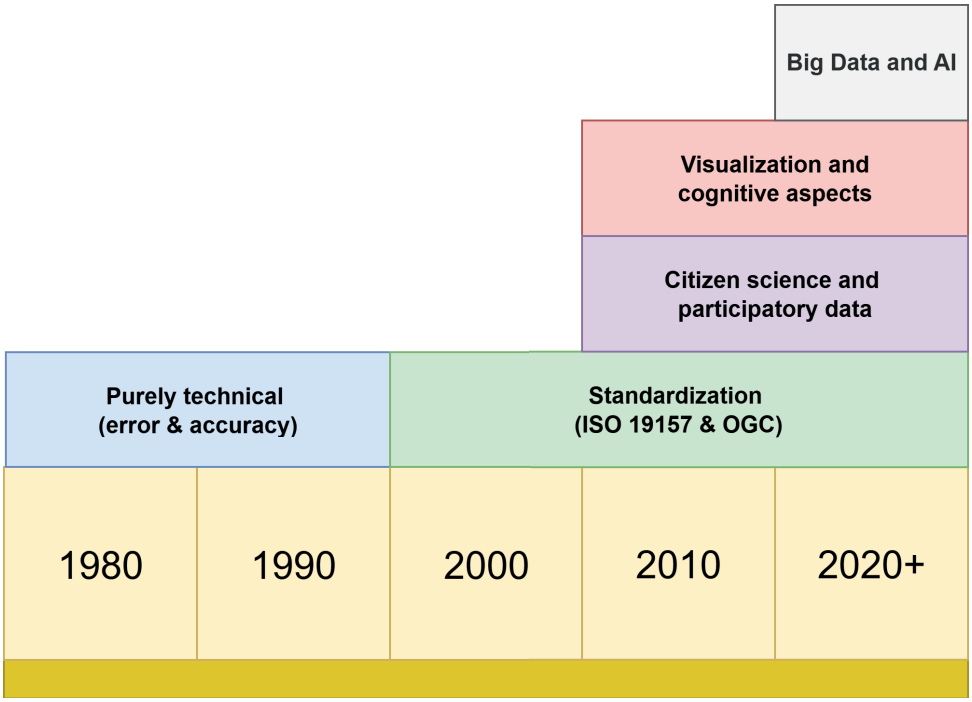


Figure 2: Evolution of approaches to uncertainty in geoinformatics and environmental sciences

Quality Frameworks and Standardization

Quality is now understood as a multidimensional concept including positional and attribute accuracy, completeness, logical consistency, temporal accuracy, data lineage, and other aspects. This classification was first systematically codified in the international standard **ISO 19157:2013 Geographic information — Data quality**, which became the basic reference framework for assessing spatial data quality (Ureña-Cámara et al., 2019). The latest revision **ISO 19157-1:2023 Geographic information — Data quality — Part 1: General principles** builts on the original ISO 19157:2013 standard and its 2018 amendment. It maintains the basic framework for spatial data quality assessment while updating terminology and expanding selected parts regarding new user needs and emerging data sources. An important element of this revision is also the division into multiple parts and a stronger emphasis on connectivity with other ISO standards, especially **ISO 19115** (metadata) and **ISO 19158** (quality assurance). While these standards provide an essential framework, their practical implementation can be complex and resource-intensive, which often poses a challenge for smaller organizations or rapid-response projects. Nevertheless, current practice increasingly relies on ISO and OGC standards, and a key principle is *fitness for use* (Devillers et al., 2007; Pôças et al., 2014), which emphasizes that data quality is not absolute but always relative to the goals we want to achieve through analysis. Practically, this means that, for example, a dataset perfectly suitable for national climate trend modeling for beekeeping may not be sufficiently accurate for local territorial prediction. Or that a digital elevation model with a spatial resolution of several meters may serve well for estimating fluvial activity in the landscape, but is unusable for modeling flooding of small pools that are key mosquito biotopes. Quality assessment must therefore always derive from a specific purpose, not from a single universal standard. Other sources confirm that the term is commonly used in connection with assessing data suitability for specific purposes (Wagner & Henzen, 2022). The "*fitness for use*" framework was, for example, described as a bridge between user needs and internal data quality (Ariza López et al., 2020). In this context, the term "chain of trust" (*Data, uncertainty and decision-making*) began to be used, showing that uncertainty arises not only in the data itself but also permeates the entire process—from data collection and processing through modeling and visualization to interpretation and decision. This concept is key to this habilitation thesis and is demonstrated in the following chapters using the author's publications, and is equally evident in applications such as flood-risk mapping (Lim et al., 2024) or seismic hazard assessment (Schneider et al., 2022), where uncertainties propagate from raw measurements through modeling to final risk-management decisions.

Participatory Data and Citizen Science

The last decade brought another **significant shift closely linked to technological development** (smartphones, web, cloud) and changing societal demand. The social and participatory dimension of working with uncertainty comes to the forefront. Citizen science projects bring extensive data volumes from volunteers, opening new opportunities and challenges. Brown and Williams (Brown & Williams, 2019) showed that with good project structure and participant training, data can achieve high quality and have real value for ecology and environmental management. Stankiewicz et al. (Stankiewicz et al., 2023) demonstrated through surface water monitoring in Luxembourg that even subjective records can be methodically processed and converted into a form usable for policy making. Callaghan et al. (Callaghan et al., 2025) document the sharp increase in citizen science use in U.S. environmental assessments —from a marginal share to almost 40% within ten years. This shows that quality and uncertainty are no longer marginal topics but direct parts of decision-making practice. The expansion of citizen-generated data accelerated the use of uncertainty in real environmental scenarios. In ecology, hydrology, or climatology, it shows how heterogeneous sources—including citizen science—enter analyses, predictive models, and simulations. It has been shown that understanding and quantifying uncertainty is crucial for their interpretation. This conclusion is confirmed by the author's studies included in the habilitation: especially work with beekeeper data and collection of information about mosquito abundance in the Litovelské Pomoraví Protected Landscape Area (PLA).

Uncertainty in Environmental Applications

The concept of fuzzy boundaries stems from **fuzzy set theory** (Zadeh, 1965) and enables converting the semantic uncertainty of natural phenomena from the modeling phase directly into visualization. Arnot and Fischer (Arnot & Fisher, 2007) applied the fuzzy approach to ecotones and showed that traditional binary classification in these zones loses critical information. Using fuzzy boundaries here serves not just as graphic innovation but directly illustrates how uncertainty can be transferred from the modeling phase to the visualization phase.

Environmental applications clearly show the crucial role of working with uncertainty (Refsgaard et al., 2007). In hydrology, uncertainty is reflected in flood risk models (Beven et al., 2015; Brandt et al., 2021) and drought predictions. In climatology, uncertainty is routinely communicated via confidence intervals and scenario ranges (Booker et al., 2025; Hawkins & Sutton, 2009; Kayusi et al., 2025). In ecology, it involves uncertainty in biodiversity data (Gadelha Jr et al., 2021; Veiga et al., 2014), protected species occurrence, and biogeographic range modeling (Tessarolo et al., 2021), where boundary vagueness (Jana & Mahanta, 2023) and record imprecision affect threat assessment or intervention. These problems clearly emerged when creating the predictive model for Asian hornet (*Vespa velutina*) based on occurrence data and climate development scenarios (Walter et al., 2024). In the context of spatial species distribution modeling, Rocchini et al. (Rocchini, 2010) demonstrated how the fuzzy approach better represents uncertainty in species occurrence prediction and what forms of uncertainty appear in various outputs (Rocchini et al., 2011).

In **public health**, uncertainty is monitored (Delmelle et al., 2022) when modeling disease vector spread, whether mosquitoes or ticks. In urbanism, consideration of uncertainty is increasingly promoted when assessing service accessibility, infrastructure planning, or vulnerability assessment (Rezvani et al., 2023). In all these areas, decisions based on data without explicit work with uncertainty can be misleading, while a transparent approach increases trust and decision quality. With growing model complexity and breadth of application areas, however, it became clear that not only uncertainty quantification itself is key, but also its comprehensible communication. This led to a shift in interest from purely analytical procedures to developing visualization and cognitive methods that enabled passing results to experts and the lay public in a comprehensible and decision-supporting form.

Visualization and Cognitive Aspects

At the turn of the millennium, there was a shift from technical error measurement to the question of how to visualize and communicate uncertainty. Plewe (Plewe, 2002) showed that for historical and environmental data, uncertainty is not just a technical problem but stems from epistemological questions of how we **conceptualize space, time, and phenomena**. MacEachren et al. (MacEachren et al., 2005) summarized available approaches to uncertainty visualization and identified seven **key challenges** that need to be addressed for uncertainty visualization to support understanding and decision-making. Thomson et al. (Thomson et al., 2005) presented a typology of visualization methods that systematically distinguished different strategies by uncertainty type and user needs. Collectively, these works marked a shift from error illustration to decision support: they began to understand uncertainty visualization as a decision support tool, not merely as an illustration of technical error. The next step was empirical verification of the visualization method's effectiveness. Deitrick and Edsall (Deitrick & Edsall, 2006) conducted experiments testing how different visualization methods affect user trust and decision-making. They showed that some visualization techniques can facilitate user understanding and increase result credibility, while others may inadvertently increase cognitive load and impair decision quality. The shift to visualization was driven not only by academic interest but primarily by the growing need to communicate complex analysis results to laypeople and decision-makers. A systematic review of methods is provided by Kinkeldey et al. (Kinkeldey, 2014), who show that visualization effectiveness depends on data type and uncertainty character. These studies opened the path to what we now consider essential: every uncertainty visualization should be empirically tested on real users (Kinkeldey et al., 2017). Eye-tracking has established itself in the last two decades as a key method for objective assessment of cartographic visualizations, including uncertainty display. Çöltekin et al. (Çöltekin et al., 2010) demonstrated eye-tracking's potential for understanding cognitive processes when reading maps. Ooms et al. (Ooms et al., 2014) showed that eye-tracking can

reveal significant differences in how experts and laypeople interpret cartographic symbols. Among the initial studies were also the author's attempts at using eye-tracking (Brus et al., 2012). An extensive study testing various uncertainty display methods in maps using eye-tracking was conducted by Kübler et al. (Kubler et al., 2020), who found that intrinsic methods (where uncertainty is integrated directly into the symbol) are more effective than extrinsic ones (separate layer). Motivated by these findings, the present thesis includes an article addressing symbol design, optimization, and testing using eye-tracking. However, most studies focus on static maps and laboratory conditions. Research on interactive visualizations and testing in real decision-making situations, especially under time pressure, is lacking. Alongside visual communication, multimodal and inclusive approaches (haptic and interactive maps) are developing that respond to user diversity and cognitive strategies.

Haptic Maps and Multimodal Communication of Spatial Data

Haptic maps represent an alternative way of communicating spatial information, especially for visually impaired users. Perkins (Perkins, 2002) provided a basic overview of haptic map creation methods. Brock et al. (Brock & Jouffrais, 2015) presented interactive haptic maps combining touch with audio feedback. Wabiński and Mościcka (Wabinski & Moscicka, 2019) analyzed automated procedures for generating haptic maps from OpenStreetMap data. Barvíř et al. also used OpenStreetMap for interactive maps (Barvir et al., 2021). Holloway et al. (Holloway et al., 2018) tested 3D printed maps and showed that different printing types affect element distinguishability. Wabinski et al. presented guidance on how to create haptic maps and standardize their creation process (Wabinski, Moscicka, et al., 2022; Wabinski, Touya, et al., 2022). Despite advanced research, systematic investigation of **how to communicate uncertainty and data quality in haptic maps** is still lacking. The question of generalization and simplification for tactile perception creates a specific type of uncertainty that is not sufficiently explored.

New Challenges: Big Data and AI

Parallel to the development described above, data volume and nature grew rapidly. In the author's research, this manifests, for example, in work with long-term climate series (1950–2025) for analyses and predictions of bee colony losses and modeling mosquito hotspots based on sensor networks. The advent of big data and AI brings new types of uncertainty—from non-transparency and difficult reproducibility to interpretation of outputs for practice—again emphasizing measurement, visualization, and integration of uncertainty into decision-making. A prominent issue is trust in AI-generated maps (Prestby, 2024). Empirical studies show that **visualizing uncertainty in AI supports higher trust** (Reyes et al., 2025). Predictive models based on machine learning bring new types of uncertainty, for example, algorithm non-transparency, result reproducibility problems, or the question of output interpretation for practical users. Weiskopf (Weiskopf, 2022) summarizes the main challenges in this context and notes that uncertainty visualization must respond not only to classic questions of accuracy and completeness but also to these new problems. In the context of the work, four challenges defined at a workshop on uncertainty to be held in November in Vienna at the IEEE VIS 2025 conference can be described. First, the visualization community still lacks sufficient understanding of how to appropriately model uncertainty and carry it through complex scientific workflows. Second, artificial intelligence (AI) is rapidly spreading across scientific fields but faces a fundamental problem—the trustworthiness of its predictions is limited by uncertainties propagating from both data and AI models themselves. Third, there are no unified and proven ways to effectively communicate this uncertainty to end users, whether expert or lay public. Finally, decision-making under uncertainty remains an open challenge, as human perception factors, cognition, and levels of expertise fundamentally enter into interpreting uncertainty. These experiences show that new approaches to big data and AI are not just a theoretical vision for environmental research but have become an essential part of daily practice across the topics this work addresses.

Summary

Critical evaluation of the literature shows that some previously common approaches proved to be less effective. Purely technical concepts of data quality based on a few metadata items did not provide users with the needed support. Participatory projects relied on large numbers of records without systematic validation, leading to biased conclusions. In visualization, overly complex map outputs that increased cognitive load and reduced decision quality proved unsuccessful. Finally, even data-rich machine learning models did not bring higher reliability where uncertainty analysis was not integrated from the beginning. These experiences were reflected in the author's own work, where it became clear that **without connecting technical, visualization, and participatory approaches, reliable results cannot be achieve[d]**.

Looking at the development of attitudes and scientific approaches to uncertainty and data quality from a greater distance, it can be understood as a journey from a purely technical concept of uncertainty to a sophisticated, multidimensional, and user-oriented approach. Despite considerable progress and the creation of a solid foundation, individual approaches often remain isolated. Moreover, they focus only on measuring technical parameters, visualization, or participatory aspects. From this perspective, a unifying concept that would systematically connect these dimensions is missing.

The review conducted revealed the following key gaps that directly lead to this work's research questions:

1. **Missing integrating concept** (→ **RQ1**): Existing approaches to uncertainty remain fragmented. Technical, visualization, and participatory aspects are addressed in isolation; a unifying user-oriented framework is missing.
2. **Insufficient methodology for heterogeneous data** (→ **RQ2**): Current research does not provide systematic guidance on working with uncertainty in different data types (expert, citizen science, interdisciplinary) within a unified concept.
3. **Absence of empirical validation of visualization methods** (→ **RQ3**): Many proposed uncertainty visualizations have not been tested on real users in practical situations. Comparison of subjective preferences with objective effectiveness is particularly lacking.
4. **Limited practical impact** (→ **RQ4**): Academic uncertainty research rarely leads to usable decision support tools. Examples of successful transformation of theoretical insights into practical applications with measurable impact are missing.

The review does not aim to provide a complete and exhaustive overview but rather to introduce readers to the issues and define the framework within which this habilitation thesis operates. In this context, the user-oriented approach developed in the following chapters appears as a logical outcome of previous development and simultaneously a necessary innovation responding to current challenges.

CONCEPTUALIZATION: A USER-CENTERED APPROACH TO UNCERTAINTY VISUALIZATION *Chapter 2*

This foundational chapter establishes the theoretical and conceptual basis of the thesis and answers RQ1: **How can uncertainty in environmental data be conceptualized from a user-centered perspective?** It **presents** the author's approach, which **shifts** the focus from a technology-oriented workflow to one centered on the user and the effectiveness of cartographic communication. The chapter **introduces** the framework created by the author, **summarizes** its three fundamental pillars, and **shows** how the framework **addresses** RQ1.

2.1 User-Centered Approach as Foundation

The chapter builds on the theoretical framework established in **"The User Centered Framework for Visualization of Spatial Data Quality"** (Appendix 1), published in 2015 in the monograph *Modern Trends in Cartography*. This work, directly derived from the author's Ph.D. thesis, defined a methodological approach for working with uncertainty throughout its entire lifecycle—from data collection to final visualization. It became the cornerstone on which the author continued to build over time and develop further through collaboration with colleagues from other fields. Interdisciplinary collaboration with botanists, zoologists, and biochemists revealed a fundamental problem: these communities do not systematically address the quality of visualization outputs. The concepts of uncertainty and data quality are too abstract for them.

Motivation

The motivation arose from an extensive review of the state of the art, which showed that although many partial methods for uncertainty visualization existed in the field, there was no comprehensive and systematic guide for correctly and effectively selecting and applying these methods. Research at that time primarily focused on describing data quality but neglected the decision-making process of the map creator, who produces visualizations for specific purposes and audiences. Working with uncertainty was thus often understood as a purely technical problem rather than a complex communication challenge. The goal was therefore to propose a conceptual model that would guide map creators through the entire decision-making process and help them create visualizations that are not only technically correct but, above all, comprehensible to end users. From the perspective of uncertainty visualization, this represents the greatest challenge**.**

Methodology

The methodological contribution of the published work lies in formulating a comprehensive, user-centered approach based on three key points:

- **Refined terminology:** One key point is distinguishing between the concepts of data quality and uncertainty. Data quality refers to measurable properties of a dataset. Uncertainty is broader—it spans the entire information chain, including how end users ultimately perceive and act on the information. The importance of standardizing these terms was recognized by the author earlier.
- **Defining quality as "*fitness for use*":** The framework is based on a definition that makes quality a relative, not absolute, property. In other words, a map or final visualization is "high quality" only if it is suitable and understandable for a specific user and fulfills its intended purpose. Visually attractive maps displaying uncertainty are often produced. The problem is that users don't understand them. This brings cognitive aspects such as education, expertise, and user experience to the center of attention. As shown when working with various groups, from beekeepers to the general public, it is sometimes more effective to create a simpler map that readers can understand, even if not methodologically perfect, than to strive for a perfect but incomprehensible visualization. Except when the goal is primarily to demonstrate uncertainty itself, uncertainty should not become the central and dominant theme of visualization.

- **Designing the decision process:** The core of the work is the decision-making process diagram itself. It reverses the traditional, data-driven procedure. Instead of starting with data, the framework directs creators to begin by analyzing the **map objective** and especially the **target user group**.

Contribution

Only after understanding for whom and why the map is being created is it possible to proceed to further steps—choosing the form, specific content, and finally the means of expression. The main result of this chapter is therefore not an empirical finding but the proposal and justification of a new methodological framework. Its interpretation is the insight that effective communication of uncertainty requires abandoning a purely technocratic approach and adopting a cognitive and communicative perspective. The framework provides a systematic guide for avoiding the creation of visualizations that are technically sophisticated but incomprehensible or misleading to target users. The author verifies this approach annually through teaching, where it became apparent that even advanced cartography students find the concept of data quality difficult to grasp and its visualization problematic. Cross-evaluations of student work repeatedly show that the simplest visualizations are perceived as the most understandable. Many map users lack formal cartographic education or training (Wikle & Sinton, 2021), so intuitiveness **remains** crucial for decisions based on spatial data.

This chapter and its theoretical framework form the foundation of the entire habilitation thesis and directly address research question RQ1. Although the chapter builds on the doctoral work, its placement at the beginning of the habilitation dossier demonstrates the author's consistent approach to communicating uncertainty, evident in all publications included in the work. It defines the core philosophy—why it is necessary to focus on the user—while the following chapters describe how to implement this approach and with which specific methods. They show how the framework was applied when solving problems with heterogeneous data (Chapter 3), how visualization methods were verified based on it (Chapter 4), and how the entire process led to creating tools with real decision-making impact (Chapter 5).

This demonstrates the theoretical validity, practical functionality, and relevance of the proposed approach, which has been repeatedly applied, tested, developed in new contexts, and implemented in practice since the dissertation was published. The author's experience shows that even in the era of automation and advanced artificial intelligence methods, human interpretation of data remains indispensable in many situations. The key insight is that uncertainty cannot be eliminated but can be systematically made visible, quantified, and communicated. This approach is transferable to other areas where experts create data under pressure of complex decisions (e.g., map interpretation, medical imaging, or crisis management). Transparent presentation of uncertainty increases data credibility in users' eyes while supporting their ability to work critically with it.

Chapter 2 thus delineated a theoretical framework (**Figure 3**) that places the end user and their cognitive ability to understand visualized uncertainty at the center of attention. The following chapter shows how this framework is applied in practice when working with various environmental data sources and demonstrates that diverse forms of uncertainty require specific methodological approaches for their identification, quantification, and visualization.

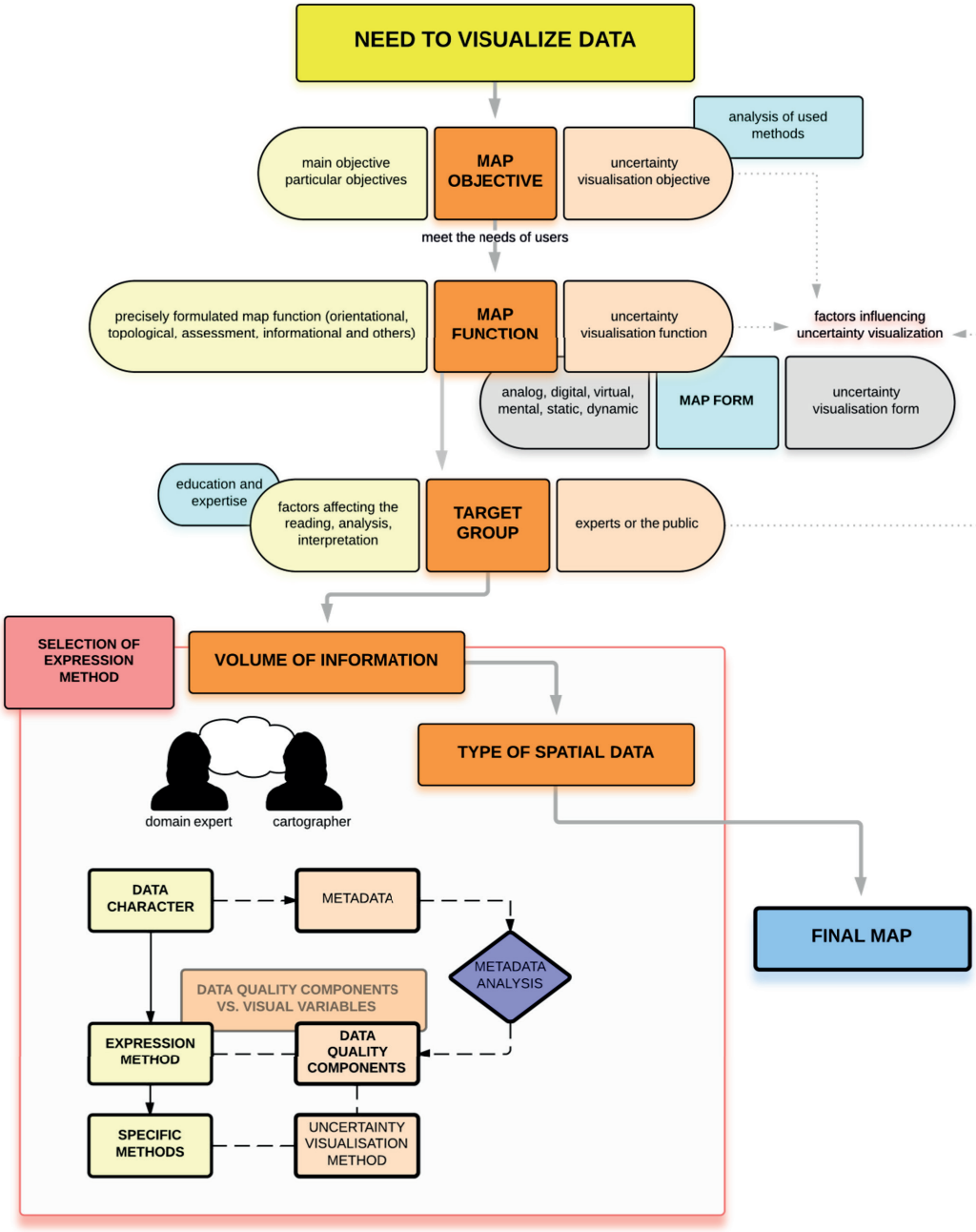


Figure 3: Proposed framework for user centered spatial data quality visualization (Brus & Pechanec, 2015)

SOURCES AND INTEGRATION: ADDRESSING UNCERTAINTY IN HETEROGENEOUS DATA *Chapter 3*

While Chapter 2 laid the theoretical foundation anchored in the user-centered approach, this chapter demonstrates its practical relevance through three distinct yet typical sources of uncertainty in contemporary environmental science. It answers the research question **RQ2: What are the sources of uncertainty and data quality in different types of heterogeneous data and how can they be methodologically addressed?** The chapter analyzes three key scenarios that demonstrate the author's ability to adapt methodological procedures to specific challenges associated with different data sources.

3.1 Uncertainty Arising from Expert Interpretation

The first analyzed source of uncertainty is the subjectivity of expert judgment—a fundamental yet often underestimated factor in data creation. This issue was elaborated in the article **"Depiction of uncertainty in the visually interpreted land cover data"** (Appendix 2), published in 2018 in *Ecological Informatics*. Despite widely available classification tools and the developing GeoAI domain, in many cases we had to rely on the abilities of the classifiers themselves, who either created training sets or directly interpreted data. However, this method was inseparably linked with human subjectivity, which affects the result.

Motivation

A clear example from recent practice is the visual interpretation of water-filled depressions used as potential mosquito breeding sites in the MOSPREMA project. Their identification is very complex; it combines a digital elevation model from airborne laser scanning with aerial imagery from the leafless period. During the atypical winter flood of 2023/2024 in Litovelské Pomoraví, receding waters created complex ice patterns in depressions. The shapes and spectral characteristics were too complex for automation. We had to interpret the data manually. Despite lengthy discussion about what is and isn't a relevant ice-covered depression, the interpretation was influenced by one expert's subjectivity. The need to unify the procedure and create an indicator of interpreter confidence proved crucial. The same issue is addressed in the mentioned study using the example of a time series of aerial images from the Heřmanice mining area. The motivation was the fact that the resulting vector maps are presented as objective and precise, even though their creation process is significantly influenced by interpreter decisions. The goal was to find a systematic way to quantify and subsequently visualize this uncertainty.

Methodology

The methodological contribution of the study, conducted on the example of a time series of aerial images from the Heřmanice mining area, lay in a systematic approach to quantifying interpretation uncertainty. In addition to digitizing land cover categories, the interpreter was required to record their **confidence** level about correct classification for each delineated polygon on a five-point scale. This procedure transformed the unquantifiable feeling of the expert into a structured attribute that could be further analyzed and mapped.

The article further emphasized the conceptual problem of the inseparability of positional and thematic accuracy, as uncertainty in boundary delineation is directly proportional to uncertainty in defining adjacent categories. This approach was subsequently successfully applied in a bachelor's thesis work (Svarcova, 2015) under the author's supervision, where the time series was extended by additional years. Various visualization methods were tested with the common goal of displaying spatial variability of uncertainty while maintaining readability of primary information. This demonstrated the possibility of visually communicating not only the data itself but also the uncertainty of its interpretation.

Contribution

The interpretation of this result was the insight that it is technically possible and beneficial for users to visually communicate expert subjectivity, which helped to a more critical evaluation of data and a better understanding of their limits. The article included results from initial user testing using eye-tracking, which suggested that methods using transparent grids and circles were rated best by experts. This procedure showed how even purely expert subjectivity can be made transparent and considered from the end user's perspective. This study thus not only answered the first part of RQ2 but also created a direct bridge to the more extensive user study presented in Chapter 4.

3.2 Uncertainty Arising from Geoparticipation and Citizen Science

This section examines uncertainties specific to public-contributed data and demonstrates a geoparticipatory workflow for mapping **mosquito outbreak hotspots** in the PLA Litovelské Pomoraví. This topic is addressed in the article **"Geoparticipation as a tool for mapping calamities mosquito hotspots: A case study from Litovelské Pomoraví, Czechia"** (Appendix 3), published in 2024 in *Environmental and Sustainability Indicators*.

Motivation

Traditional expert monitoring of mosquito populations was demanding in terms of personnel, time, and finances, and provided data from only a limited number of locations. The primary monitoring source in Litovelské Pomoraví PLA uses an application developed on the Mergin Maps platform, where field workers recorded data about mosquito numbers and their developmental stages. This expert activity is already burdened with uncertainty associated with determining exact numbers and developmental stages, which is a weak point of the entire system that must be addressed through special training and is time-consuming. However, the biggest problem is finding sufficient human resources for area-wide monitoring.

Despite the possibility of objectifying imago numbers using CO_2 traps, management strategies always encountered **subjective perception** of mosquito outbreaks by residents. The calamities themselves, as well as their perception, represent a serious socio-economic problem that negatively affects quality of life and tourism. The motivation for this study, which was a key part of the MOSPREMA project (MOSPREMA, 2025), was to develop and verify a methodology that would utilize the potential of geoparticipation and local knowledge of residents for detailed mapping of risk areas. The goal was to transform their subjective experience into a reliable foundation for decision-making schemes and management measures (**Figure 4**).

Methodology

The methodological contribution lay in creating a comprehensive procedure for collecting, processing, and validating data that are inherently subjective and qualitative. Data collection was conducted in collaboration with colleagues from the Department of Development and Environmental Studies through an online geoparticipation platform (pocitovemapy.cz), where respondents could directly draw points and polygons on the map representing places of perceived increased mosquito activity. The questionnaire further distinguished between spring and summer calamities. To transform this data into analytically usable form, several innovative solutions had to be developed:

- **Quantification of subjectivity:** Verbal assessments of activity level ("low," "rather high," "high") were converted to a numerical index.
- **Spatial aggregation:** Dozens of individual and often overlapping records from different respondents were spatially aggregated. In areas of overlap, an arithmetic mean was used to achieve a compromise value. The respondent's status (permanent resident vs. tourist) was also considered during interpretation.
- **Integration with objective data:** A key step in increasing model robustness was integrating this "perceived activity" layer with objective spatial data, such as created population density layers, population presence based on mobile operator data during day and night, and especially the location of known mosquito breeding sites. This created a final location risk model that is more reliable than any of these data sources alone.

Key results and their interpretation

The study created detailed maps of risk "hotspots" and quantified the number of residents threatened by given seasonal mosquito calamities. One of the main findings was confirmation of the hypothesis that summer calamities have a spatially more extensive impact and affect more residents than spring ones. Interpretation of the results leads to the conclusion that the geoparticipation approach is a valid and highly effective method for monitoring environmental phenomena closely linked to human perception. The resulting maps serve not only as academic confirmation of the methodology but represent a direct and practically usable foundation for decision-making processes within integrated landscape management.

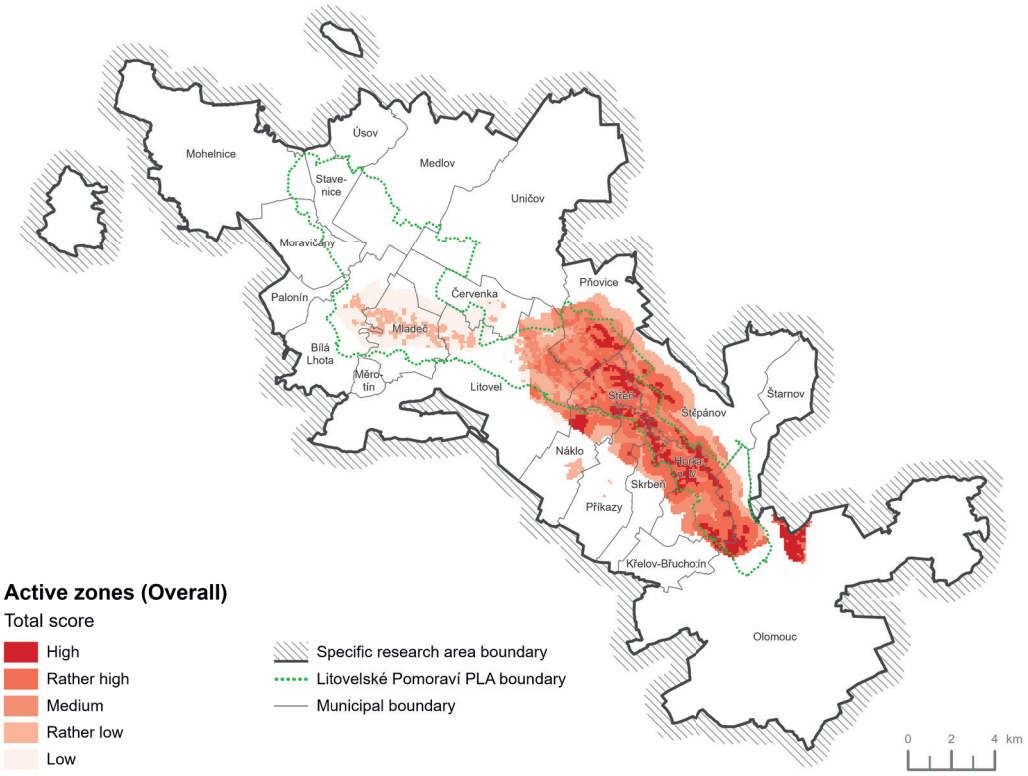


Figure 4: Overall spatial distribution of active zones (delineation by respondents' drawing and actual breeding grounds locations) (Rypl et al., 2024)

Broader context

The author has long worked with citizen science also in the COLOSS project where is collecting data from beekeepers on an international scale. COLOSS (Prevention of honey bee COlony LOSSes) is an international association and monitoring project devoted to standardizing methods for assessing winter losses of managed honey bee colonies and investigating risk factors such as operation size, queen replacement, and migration (Carreck et al., 2025). Through more than a decade of collaboration, data is collected annually in dozens of countries using unified electronic questionnaires. In the Czech Republic, we established cooperation with the Ministry of Agriculture, which allows comparison of beekeeper-reported data with official statistics and thus determination of **data representativeness**. This concept, which explicitly works with the uncertainty of the sample, was adopted after presentation to the beekeeping community and became a standard part of annual result reporting. This approach not only increases the quality and transparency of presented data but also stimulates international discussion about the relevance and reliability of data collected in other countries that don't perform similar validation. A detailed description of the COLOSS project is provided in Chapter 5.

Contribution

This study from Litovelské Pomoraví, along with the context of long-term work on COLOSS data, directly answered the second part of **RQ2**, which asks about manifestations of uncertainty in citizen science data. It is an exemplary application of the user-centered approach, where citizens are not just passive recipients of information but active creators. The work demonstrates the complete cycle "from citizens to science and back." Collecting subjective data, transforming them through rigorous scientific methodology into reliable information, and returning results back to the community in the form of a foundation that can improve their quality of life or hobby. It shows how reliable and practically valuable signals can be extracted from data with high subjective uncertainty. The study confirms that subjective citizen perceptions can be transformed into analytically usable information sources if systematic transformation and validation are ensured during the process. The main lesson is that citizen data are not just a supplement but can become a full-fledged layer in decision-making processes—if combined with objective indicators and set within a user-centered framework. This principle is easily applicable in other domains such as mapping climate change impacts, air quality, or urban noise. An added value is bidirectional communication with the community, which strengthens trust and supports data collection sustainability. Increasing trust can be demonstrated by the constantly growing number of beekeepers, reaching 9,000 in the last round. This number represents 12% of all beekeepers in Czechia, making the dataset much more informative. However, this state could not have been achieved without organizing seminars, creating web applications, and providing feedback.

3.3 Uncertainty Arising from Interdisciplinary Integration of Spatial Data

The third and most complex scenario of working with uncertainty involved interdisciplinary synthesis, where uncertainty appeared not only in the data but also in the very definitions of studied phenomena. This research challenge is addressed in the review study **"How Could the Use of Crop Wild Relatives in Breeding Increase the Adaptation of Crops to Marginal Environments?"** (Appendix 4), published in 2022 in *Frontiers in Plant Science*.

Motivation

The motivation for this extensive study was the growing need to ensure food security in the context of climate change, with one key strategy being breeding crops adapted to so-called marginal territories or lands (**Figure 5**). Success requires understanding the relationship between genetic properties of plants and environmental conditions where their wild relatives occur. The goal of the geoinformatics part was to provide a robust methodological foundation for this connection.

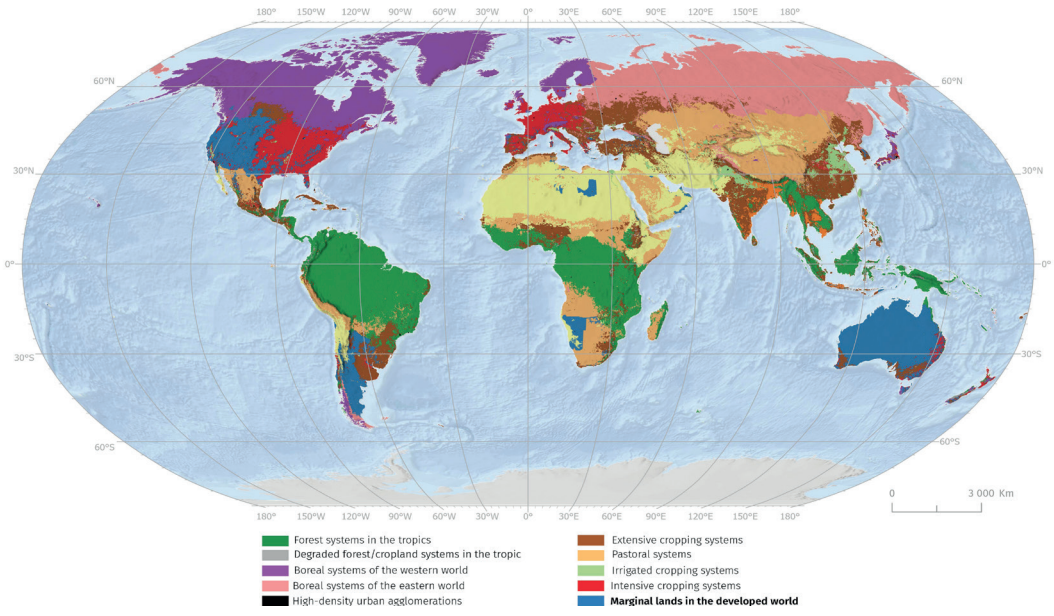


Figure 5: Global land system archetypes classification by Václavík et al. (2013); Within the global scale, marginal lands in the developed world cover about 9% of terrestrial ecosystems (Renzi et al., 2022)

The main contribution in the context of the habilitation thesis is addressing several interrelated levels of uncertainty and data quality: ambiguity, vagueness, and positional accuracy. The primary challenge was **ambiguity** in the very definition of "marginal environment." As stated in the article, this term is difficult to define as it encompasses a wide range of constraints, and its delineation depends on context and purpose. This is a typical example of the mentioned **ambiguity**, where understanding the meaning of a category encounters different definitions among authors. This ambiguity is directly followed by the problem of **vagueness**, because the spatial delineation of these territories is complicated; their boundaries are not sharp but rather form transition zones.

Methodology

Working with this concept therefore required careful synthesis of various spatial datasets (climatic, soil, topographic) to at least approximate these fuzzy criteria. Besides these conceptual types of uncertainty, solving a key problem at the data level was necessary for the study's success—low **positional accuracy** of plant occurrence records, which often suffer from rounded coordinates or gross errors (Guerra-García et al., 2024; Hradilova et al., 2019; Renzi, Brus, et al., 2020; Renzi, Duchoslav, et al., 2020; Smykal, Hradilova, et al., 2018; Smykal, Trneny, et al., 2018). In response to this problem, which is ignored by much of the scientific community, a rigorous methodological procedure was applied. This included data cleaning, geocoding, reverse geocoding, and especially the use of compensating buffers whose size was derived from coordinate quality for more robust extraction of environmental data. Similar procedures were followed in other related studies, where integration of climate data and other environmental variables required addressing issues of different scales and data synthesis. Applying this multiphase approach led to creating a more reliable analytical connection between genotype and environment.

Contribution

By correctly addressing various types of uncertainty and accuracy problems, it was possible to formulate more valid conclusions about plant adaptation. The interpretation of this finding is that geoinformatics expertise in uncertainty and data quality management is absolutely crucial for the quality of modern interdisciplinary research. This study answers the most complex part of **RQ2**. By entering the role of methodological guarantor, the author was able to address uncertainty and data quality at multiple levels—from basic technical (positional accuracy) to high conceptual (ambiguity and vagueness). This confirmed that working with uncertainty in these types of studies is essential for success in other scientific fields and confirms the broad applicability of the proposed concept.

The **three presented scenarios** demonsrated that uncertainty in heterogeneous environmental data manifests in various forms—from subjectivity of expert interpretation, through variability and subjective bias of citizen science, to conceptual and technical challenges of interdisciplinary integration. In each case, methodology had to be adapted to the specific source of uncertainty and tools created that enable its identification, quantification, or mitigation of its manifestations. The common denominator of all three approaches is geoinformatics expertise, which provides a framework for transforming diverse and uncertain inputs into more reliable and practically usable outputs. The chapter thus demonstrated that the ability to systematically work with uncertainty is a key component of modern environmental research and that the proposed methodological concept has broad relevance across fields and application areas.

The analysis of three scenarios in Chapter 3 demonstrated that uncertainty and data quality issues are integral parts of heterogeneous environmental data and that their nature varies significantly by source and context. Chapter 4 builds on this experience, focusing on the key step—how these insights can be transformed into specific visualization methods and how to empirically verify their effectiveness in communicating uncertainty to end users.

VISUALIZATION: FROM PRACTICAL APPLICATION TO EXPERIMENTAL VALIDATION

Chapter 4

The previous chapter demonstrated the breadth and complexity of uncertainty sources and data quality in environmental data. This chapter focuses on the next key step: developing, applying, and above all, verifying visualization solutions that can effectively communicate this uncertainty and data quality. The aim is to answer the research question **RQ3: How can we design and validate visualization methods that effectively communicate uncertainty and data quality to end users?** The argument is built on two complementary pillars reflected in articles that together present creative design and subsequent scientific validation. Both articles stem from the initial idea of presenting data in a form that is understandable, intuitive, and leads to better presentation and understanding of the presented data. Chapter 4, therefore, connects the theme of quality and uncertainty through two complementary parts. The first part (4.1) demonstrates the practical application of the proposed framework in the interdisciplinary environment of biogeography and shows how innovative visualization approaches can improve uncertainty communication in scientific studies. The second part (4.2) follows this application with systematic empirical validation that verifies the effectiveness and intuitiveness of chosen methods through user experiments. Together, both parts form a logical whole.

4.1 Uncertainty Visualization in Biogeographic Range

The first pillar of this chapter demonstrates the ability to apply principles of uncertainty visualization in a new, specific context where the author's contribution lay in cartographic processing of research data and better presentation to the scientific community. An example is the study **"Click beetle larvae from Cretaceous Burmese amber represent an ancient Gondwanan lineage"** (Appendix 5), published in 2025 in the Scientific Reports.

Motivation

In biogeography, the standard practice is to display species distribution ranges using sharply bounded polygons or discrete points. However, this approach is problematic as it distorts the reality of ecological niches, which are inherently vague. This is especially true for poorly studied and rarely collected insect lineages like **Elateridae** (i.e., click beetles) subfamily Pityobiinae, where occurrence data are valuable and geographically very limited. At the same time, the overall distribution is highly uncertain, and a traditional map with sharp range boundaries represents a potentially misleading representation of data (**Figure 6**). While entomologists can work with such data, the resulting map is a much better medium for spatial understanding than presenting data in tables. For this reason, the motivation for the cartographic part of this study was to create a visualization that would better communicate this natural vagueness and uncertainty of distribution range delineation.

Methodology

The methodological contribution in this work lies in the targeted application of **fuzzy boundary visualization methods** for displaying distribution zones of individual species. Unlike the traditional approach, the range was not displayed as a homogeneous area. Instead, a visualization based on a color gradient was used, implying a core zone with high occurrence probability (near verified finds) that gradually weakens toward the edges. This approach visually communicates that the range boundary is not absolute but represents a transition zone with decreasing probability. This approach is key for communicating uncertainty and fulfills the principles of user-centered design, where the goal is to provide the most valid information to the end user—in this case, a scientist from another field. This work identified an ancient Gondwanan evolutionary lineage based on larval findings in ca. 100 million years old Burmese amber. To place this significant paleontological discovery in a broader biogeographic context, it was necessary to create a comprehensive distribution map for the subfamily Pityobiinae, where the newly discovered larvae were placed by experts. As stated in the article, the map's goal

was to "summarize all known locality records and enable better understanding of individual species distributions." In this case, too, cartographic visualization is a tool for working with uncertainty—this time with uncertainty arising from incomplete and spatially fragmented occurrence data. The approach was previously implemented also in the publication focusing on another rarely collected click-beetle genus *Euanoma* (Packova et al., 2024).

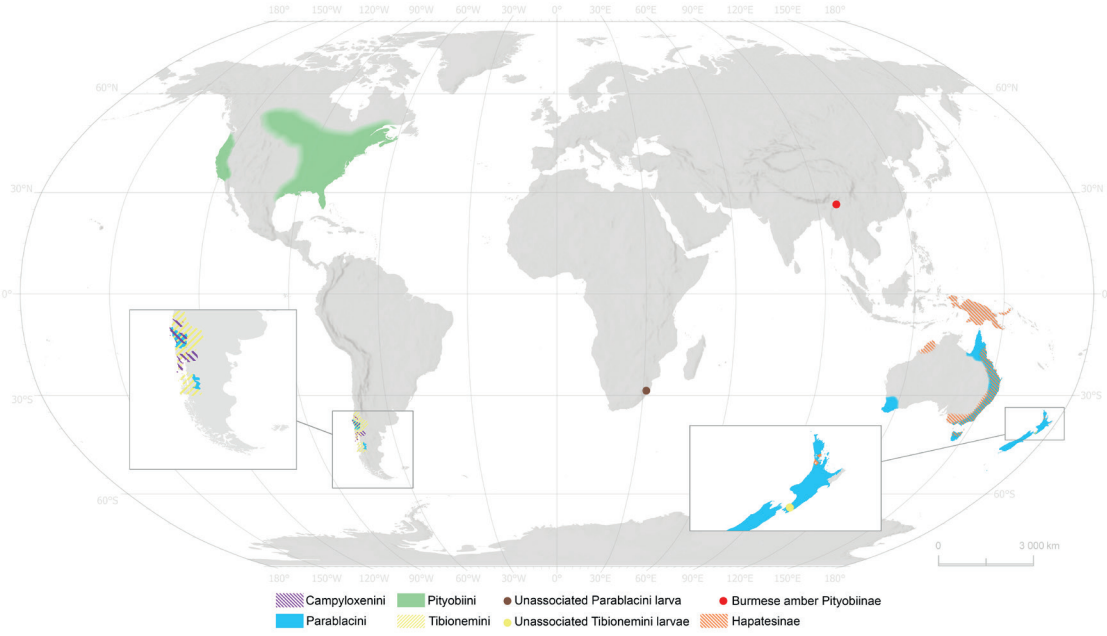


Figure 6: Distribution map of Pityobiinae and Hapatesinae, including the fossil records (Kundrata et al., 2025)

A similar approach was applied by the author in a study on distribution patterns and ecology of wild garlic (Duchoslav et al., 2020). When reconstructing the historical distribution of *Allium paniculatum* during the last glacial maximum (LGM), the authors encountered **the problem of incomplete data**, where the northern range boundary was derived from indirect sources such as permafrost position and glaciation. This uncertainty in boundary delineation was presented using a dashed line in areas with missing data, which clearly visually communicates that this is an estimated rather than directly documented information. This simple yet fundamental form of data communication is an example of effective and transparent uncertainty communication that again confirms the proposed methodological procedure.

Key results and their interpretation

The results of both studies are maps that provide **richer and scientifically more accurate information** than standard distribution maps or occurrence boundary maps. Users receive not only information about the approximate location of the range or boundary but also visual cues about the uncertainty of its delineation. This form of map serves better visual presentation of actual species distribution and can more effectively guide future research. The interpretation is again the claim that applying correct geovisualization principles can fundamentally increase the information value and scientific quality of outputs in related fields.

Contribution

The presented studies are the first part of the answer to **RQ3**. They demonstrate the ability to practically apply user-centered philosophy to a specific problem and choose an appropriate visualization method for it. They are an example of how geoinformatics and cartographic expertise bring added value to other scientific disciplines and how methodologically innovative approaches to uncertainty communication can be promoted even within primarily field-specific articles.

4.2 Empirical Validation: Measuring Effectiveness of Uncertainty Visualizations

The second pillar of this chapter represents a qualitative shift from method application to their systematic and objective validation. It is based on the study **"Intuitiveness of geospatial uncertainty visualizations: a user study on point symbols"** published in 2019 in the journal Geografie (Appendix 6).

Motivation

As indicated in the author's previous research and confirmed in the literature review of this habilitation thesis, many proposed methods exist for uncertainty visualization, but only a minimum have undergone rigorous **user testing**. When studies exist, they often contain only small numbers of respondents and don't simulate real conditions under stress. Recommendations for uncertainty visualization were therefore often based on theoretical assumptions or subjective preferences rather than real data about how users understand visualizations and how effectively they can work with them. The motivation of this study was to fill this gap and move from proposals to objective, data-based evaluation of effectiveness and intuitiveness.

Methodology

The main pillar of this study lies in deploying an objective method of measuring user interaction using eye-tracking technology to collect objective data about user behavior when solving tasks on maps with visualized uncertainty. Before the actual testing, a questionnaire was created containing symbol proposals for presenting uncertainty. One hundred respondents indicated which symbols they found intuitive and which not. Subsequently, the best and worst rated symbol proposals were used in experiment preparation to confirm the hypothesis that the best-rated proposals may not work when solving specific tasks. For the mentioned objective testing, forty respondents were selected (divided into experts and laypeople) who completed a specific task. Participants selected three optimal sites for camera-trap placement based on symbols encoding different uncertainty levels. The goal was to solve a specific task that required working with presented uncertainty, and wildlife occurrences to be captured on camera traps were represented with different degrees of uncertainty. Users therefore had to make decisions and it was up to them whether to include uncertainty in their decision or not. Unlike questionnaires that only determine subjective preferences. Eye-tracking captured performance and cognitive load (scanpath length, trial time, fixations). The experiment systematically tested **various visual variables** (e.g., blur, color saturation, size, shape) and two different legend designs.

Key results and their interpretation

The study brought several fundamental findings. The key result was confirmation of the hypothesis that **subjective user preferences for a given symbol did not equal their real performance** when working with it. For example, symbols using blur (fuzziness), which respondents rated as very suitable in the initial questionnaire, performed averagely in practical tasks, while less preferred symbols using color saturation were among the most effective. This proves that the effectiveness of visual variables is strongly context-dependent. The study also provided strong evidence that integrated legend design, where uncertainty is directly part of the symbol, is more intuitive for users and enables faster information processing. Analysis using the ScanGraph tool (Dolezalova & Popelka, 2016) additionally revealed no significant differences in map reading strategies between experts and laypeople for this type of task.

Contribution

This work is the second and key part of the answer to **RQ3**. It represents empirical validation of principles proposed in Chapter 2. This way it is possible to directly prove that the user-centered approach is an important concept and needs to be verified experimentally. Based on the results, it is possible to demonstrate that there is no universal symbol set for uncertainty visualization for all scenarios. Also, it was confirmed that the very concept of uncertainty is mostly ignored by users from other fields, and even when the concept is explained, the perception of uncertainty visualizations is very user-dependent. Here we can recall work with beekeepers, where to find a suitable visualization method we conducted both questionnaire surveys before and after symbol design. Moreover, we moved from static presentation forms to interactive web forms where users can work with uncertainty and choose themselves how uncertainty will be visualized.

Chapter 4 shows that the user-centered approach to uncertainty visualization can not only be creatively applied in interdisciplinary contexts (4.1) but also systematically and empirically verified (4.2). Both pillars complement each other: while application in entomology and botany demonstrates the practical relevance of proposed methods, the user study provides objective evidence of their effectiveness and intuitiveness. Together these results confirm that uncertainty visualization is not just a theoretical question of cartographic design but represents a practically usable tool that can increase decision-making quality in various application areas. This creates a direct bridge to Chapter 5, which demonstrates the practical impacts and broader applicability of this approach.

APPLICATIONS AND IMPACT: FROM MANAGEMENT TO INTERACTIVE TOOLS *Chapter 5*

While the previous chapters laid the theoretical foundation, examined sources of data uncertainty, and validated visualization methods, this chapter demonstrates how the proposed user-centered framework can be applied to real-world problems. It answers the research question **RQ4: How can systematic work with uncertainty and data quality contribute to creating practical tools and supporting decision-making in environmental and societal contexts?** The aim is to demonstrate through different case studies that the presented research framework of the habilitation thesis is applicable at various scale levels and for diverse target groups, always leading to tangible outputs with high added value.

5.1 Decision Support in Beekeeping

The first application domain focuses on decision support at the macro level of international management in honeybee (*Apis mellifera*) husbandry. It is based on two related publications analyzing data from COLOSS international monitoring: **"Comparison of apiculture and winter mortality of honey bee colonies (*Apis mellifera*) in Austria and Czechia"** (Appendix 7) and the manuscript **"Varroa control strategies of different beekeeper groups and corresponding honey bee colony mortality in Central Europe"** (Appendix 8). The second publication (Appendix 8) is under review for publication in the Journal of Advanced Research. As mentioned in previous chapters, the author has long worked with beekeepers and is part of the monitoring group within the COLOSS association. For this reason, several studies have analyzed colony management strategies, including treatment and husbandry practices. The data reveal numerous insights, but they show that working with uncertainty and data quality is a key concept. Moreover, in international comparisons, it is necessary to validate the informative value of data and compare comparable things, as respondent numbers vary considerably across countries and especially regions, and pure percentage expression without weighting relevance leads to completely misleading results. The problem is serious. These inaccurate figures influence political decisions in the EU and individual states. Therefore, data presentation in this case is crucial for objectifying the problem.

Motivation

High winter colony losses represent a serious **ecological and economic problem** monitored across Europe. Besides climate change and the difficult prediction of the beekeeping year, invasive species that significantly affect beekeeping practice are to blame. Whether we're talking about the Varroa mite (*Varroa destructor*) or the Asian hornet (*Vespa velutina*), it's a pan-European problem with enormous impact on individual beekeepers as well as the entire economy associated with honeybee husbandry. The key to solving this problem is understanding seasonal dynamics, invasive species behavior, and specially creating management practices that lead to lower interannual colony losses. To propose better and more suitable strategies, we need to collect and monitor data about these practices over time. As mentioned several times, data are obtained through questionnaires from tens of thousands of individual beekeepers, representing an **enormous, heterogeneous, and inherently uncertain dataset**. The motivation of the studies was to analyze this complex dataset to find effective management strategies that could be recommended back to the beekeeping community and help reduce losses caused by the aforementioned factors.

Methodology

The first study (Appendix 7) used statistical and spatial analysis to compare beekeeping practices between Austria and the Czech Republic. In this study, we tried to present and compare results objectively both visually and through data analysis. For comparison purposes, both official statistical data on the number of beekeepers and colonies and questionnaire survey results were used, with outputs visualized for both countries. This approach enabled objectifying findings while illustrating differences in respondent participation: in Austria,

respondents comprised about 6% of all beekeepers, while in the Czech Republic, only about 1.5%. The visualization thus clearly showed disproportions between both countries while highlighting the limited representativeness of data resulting from different questionnaire return rates. The study also pointed out that although conditions in Austria and Czechia are quite similar in terms of landscape and environment, the structure and intensity of beekeeping differ—Czechia has significantly higher numbers of beekeepers and colonies, leading to higher colony density per capita. These differences must be considered when interpreting winter losses and searching for their causes. The authors emphasize that quality and reliable conclusions can only be made when official statistics are combined with data from standardized questionnaire surveys. Questionnaire surveys alone don't have sufficient informative value if not placed in a broader context. It is therefore necessary to reflect different respondent return rates in individual countries. For decision-making practice, this means that loss assessments cannot be mechanically transferred between states but must always be placed in the context of national beekeeping structure and quality data availability. The study thus provides an important framework for evidence-based decision-making in colony protection and beekeeping support policy. These claims are consistent with the results of another study that found very different beekeeping strategies across Europe (**Figure 7**) that nevertheless led to similar winter loss values (Brodschneider et al., 2022).

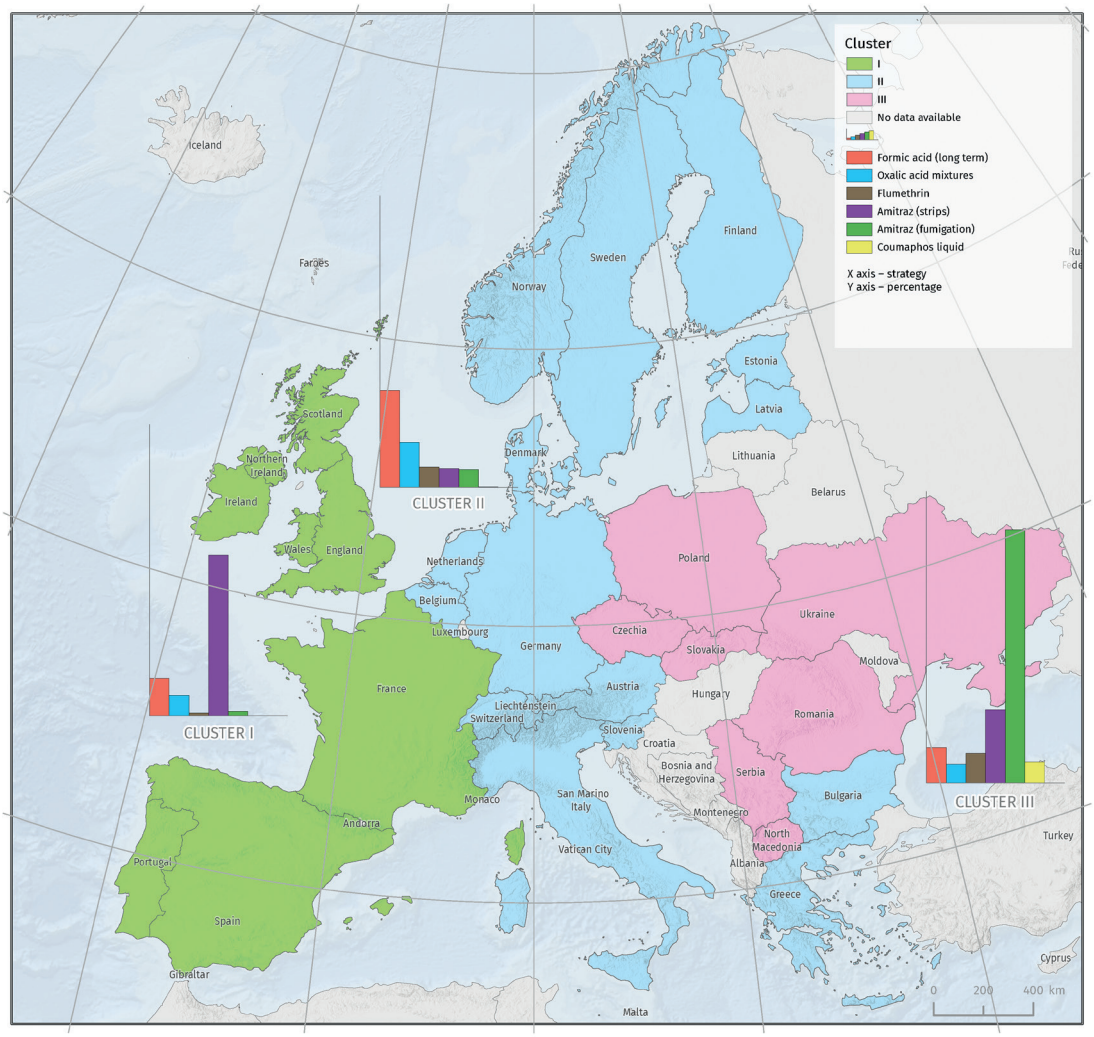


Figure 7: Spatial representation of the three Varroa control clusters identified in Europe. Inserts show the magnitude of application of the six Varroa control methods identified to be significant for cluster forming and are shown on the same scale (Brodschneider et al., 2022)

The second study (Appendix 8) advanced the analysis by a crucial step. In this study, the author and team wanted to find optimal procedures leading to reduced colony losses through pattern analysis of strategies. The methodological innovation here was applying decision tree analysis to such an extensive dataset. This

technique enabled extracting the most significant factors from complex data and identifying specific, seasonally timed combinations of procedures that demonstrably led to the lowest losses. Although four countries and different "operational" sizes of beekeepers were compared, strategies were found that led to a significant reduction in colony losses at various levels. Throughout the work, data were filtered with emphasis on quality and comparability. The study results include map outputs and decision trees where the user approach was fully applied for better data understanding and objectification of findings.

5.2 Tools for Invasive Species Management and Local Problems Management

The second block of applications focuses on **creating specific tools and models for decision support** at national and local levels. An example is creating a predictive model for Asian hornet spread (Walter et al., 2024). The first confirmed finding of the highly invasive Asian hornet in the Czech Republic, which came from public reporting, triggered an acute need for a quick and targeted response to prevent its further spread. Even before the finding, due to concerns about future spread, a predictive model was developed to identify areas in the Czech Republic most suitable for its establishment and serve as a basis for targeted monitoring. Qualitatively cleaned databases of European finds (GBIF, iNaturalist) were used as study input and subsequently used as input to a maximum entropy model (Maxent), which modeled habitat suitability for the specific species based on bioclimatic variables. The result is a map predicting areas with the highest risk of hornet spread, serving as a direct tool for decision support for the Nature Conservation Agency of the Czech Republic and other authorities. This study is another strong example of how combining public data with advanced spatial modeling can generate critically important insights for biodiversity protection.

The last example is an application focused on local government and the development of a specific software tool. It is based on the contribution **"Design of decision support tools for the quality assessment of illegal dumping notifications based on crowd-sourced data"** (Appendix 9). The motivation for this work was the growing popularity of citizen science mobile applications (e.g., ZmapujTo), where municipal offices face the problem of large numbers of reports from citizens whose quality and accuracy are highly variable. From an efficiency perspective, verifying every report in the field is inefficient. The motivation was therefore to design a tool that would help local government sort and prioritize this information load more efficiently. The work also served as a methodological and conceptual input for optimizing the Mergin Maps application used for collecting information about mosquito larvae abundance, mentioned in Chapter 3. The innovation lay in designing a decision support tool that semi-automates the assessment of report quality. The methodology is based on using a maximum entropy model (Maxent) trained on data about already verified dumps and relevant environmental variables. This model can calculate the spatial probability of correctness for each new citizen report. The result is therefore a model that assigns a reliability score to each new report and enables more efficient resource allocation and prioritization of records by local government.

Contribution

This block of work further illustrates and develops the cycle "from citizens to science and back" described in Chapter 3. Data provided by citizen-experts are processed using **advanced analytical methods** and results are returned to the community in the form of practically usable recommendations and decision-making foundations. Based on these studies, it is possible to demonstrate that geoparticipatively collected data containing uncertainty can be used to generate results for direct decision support. The studies thus provide a direct answer to the part of **RQ4** that asks about creating specific decision support tools (Pechanec et al., 2015) and demonstrate how analysis and modeling with included uncertainty can solve practical problems across the entire spectrum of application domains.

5.3 Innovation in Communication and Information Access (Haptic Models and Maps)

The third pillar represents the ultimate application of the user-centered approach. It is based on a research line dedicated to haptic maps and interactive models, represented by the articles **"Efficient Interactive Tactile Maps: A Semi-Automated Workflow Using the TouchIt3D Technology and OpenStreetMap Data"**

(Appendix 10) and **"Creating a Haptic 3D Model of Wenceslas Hill in Olomouc"** (Appendix 11). The motivation for this research direction was long-term collaboration between the author and the Institute of Special Education Studies at Palacký University Olomouc in overcoming the limits of purely visual communication of spatial information, especially in the context of education, museums, and making cultural heritage accessible to people with specific needs, such as visual impairment.

Methodology

The Department of Geoinformatics at the Faculty of Science Palacký University Olomouc has long been involved in creating haptic maps, and the author has been actively engaged in 3D printing since 2014. This connection made it possible to innovate the entire approach to haptic maps. The key innovation was the **TouchIt3D** technology developed by the author, which uses multi-material 3D printing to create interactive physical models. Models are created by combining conductive and non-conductive plastic and are subsequently connected to a touch device. This approach enables simultaneous use of touch and hearing, thereby increasing accessibility of spatial information to a broad spectrum of users. If users are visually impaired, contrasting colors can also be used to support the technology and distinguish individual model parts. The research also found a semi-automated procedure for more efficient creation of haptic maps using OpenStreetMap data, bringing a much more scalable solution (Appendix 10).

A specific contribution of this research line in the context of the work is also explicit work with uncertainty in communicating spatial information. While in regular maps, visual interpretation of ambiguities can be largely compensated by user experience, in haptic form, uncertainty needs to be addressed directly in the model design, and the model must be prepared with emphasis on the user. From a modeling perspective, these are situations where relief features must be simplified to be recognizable by touch, leading to generalization and thus raising the question of uncertainty: which part of the model can be suppressed or conversely emphasized. In accordance with the claim that all models are wrong, but some are useful, this saying takes on concrete meaning. Subsequent use of different materials and textures introduces **semantic uncertainty**—the user must correctly connect the symbol and its meaning. Tactile perception has lower spatial resolution than vision, making **generalization choices** pivotal. User testing identified which details remain legible by touch and where **audio augmentation** best reduces **semantic uncertainty**. A crucial finding was that interactive models combining touch with accompanying audio tracks can significantly reduce this uncertainty and facilitate correct data interpretation, supplementing information that couldn't be captured in the model any other way. The technology also offers the possibility of language mutations, and with the new era of AI, dynamically generated content. This block thus demonstrates that the user-centered approach to presenting uncertainty and data quality can lead not only to decision support tools but also to completely new forms of information access.

Contribution

This research is supported by several projects funded by the Technology Agency of the Czech Republic and is the subject of a utility model. In the habilitation thesis, this research represents the ultimate manifestation of the user-centered approach from Chapter 2, as it shows the possibility of transferring work with uncertainty to other domains and bringing innovative **solutions** in spatial information communication. It thus answers the part of RQ4 that aims at generating insights in societal contexts and shows that work with uncertainty can have a direct impact even in areas outside environmental sciences. We were recently invited to contribute to a world-leading publication on tactile mapping, published by the prestigious Esri Press, which represents one of the highest achievements attainable in our field (Altena & Wabiński, 2025).

The presented examples illustrate that the scientific framework of the habilitation thesis has a practical impact from data analyses and management strategies (beekeeping), through creating predictive models and software tools (invasive species, illegal dumps), to innovations in communication and information access (visualization and haptic maps). The common denominator everywhere is **systematic work with uncertainty**, which is reflected in ways of data representation, their application, and final impact on decision-making practice and society. The habilitation thesis thus fulfills its title: it connects the study of uncertainty and data quality with visualization and haptic communication methods and shows that their comprehensible presentation can serve as a bridge to better environmental decisions.

These diverse applications—spanning from data-driven decision support to innovative accessibility solutions—demonstrate that **the user-centered approach to uncertainty extends beyond traditional environmental analyses**. The TouchIt3D technology particularly exemplifies how uncertainty considerations can drive innovation in unexpected directions, making spatial information accessible to previously excluded user groups. With these practical demonstrations of the framework's versatility established, we now turn to a critical synthesis of the findings, examining both the broader theoretical implications and the limitations encountered throughout this research.

DISCUSSION *Chapter 6*

The discussions for each particular study are presented within the articles. However, the purpose of this overall discussion is to address the **broader challenges and limitations** of the habilitation thesis. This habilitation thesis, based on eleven scientific studies, develops and demonstrates a comprehensive user-centered approach for working with uncertainty in environmental analyses. The presented examples and procedures—from theoretical conceptualization (Chapter 2), through analysis of real data problems (Chapter 3), development and testing of visualization solutions (Chapter 4), to demonstration of real impact on decision-making processes (Chapter 5)—confirmed that a systematic approach to uncertainty and data quality is not only theoretically justified but, above all, practically functional and beneficial. Thus, the thesis presents and validates a unified framework rather than a heterogeneous mosaic of individual publications. This chapter critically synthesizes the main findings, points out limitations, and indicates broader impacts, possible extensions, and future directions.

This body of work, based on the presented publications, demonstrates that managing uncertainty throughout processing, analysis, and visualization is not merely supplementary but is a prerequisite for meaningful application. The combination of user approach, empirical testing, and standardization forms a unified methodology that extends beyond the examples presented here. Properly grasped uncertainty thus ceases to be a weakness of studies but becomes an effective tool for more responsible decision-making. The methodological contribution of the work lies in creating, applying, and empirically validating a comprehensive **user-centered approach** for working with uncertainty in spatial context. This framework is built on three key pillars:

Systematizing the management of heterogeneous uncertainty sources, where specific procedures were developed for transforming heterogeneous data—from quantifying subjectivity in expert interpretation, through objectifying data arising from citizen science principles, to addressing semantic vagueness and positional accuracy in interdisciplinary research. The second pillar is **empirical validation of uncertainty visualization and communication**; here not only were new visualization methods like fuzzy boundaries in biogeography applied, but their effectiveness was objectively verified through eye-tracking technology, leading to a crucial finding: subjectively preferred visualizations are not necessarily those that perform best in tasks. T**ranslating methodology into practice through concrete tools**, where specific decision support tools were designed (for invasive species management and local problem reporting) and an entirely new communication platform (TouchIt3D) was developed, demonstrating the broad applicability and societal impact of the entire approach.

In this sense, the presented approach can be understood not merely as a collection of case studies but as a methodological contribution bridging traditional technical geoinformatics with new directions in environmental research based on interdisciplinarity, user testing, and bidirectional communication between science and practice.

Theoretical Grounding of Results

The obtained results can be viewed within the broader framework of geoinformatics and environmental science development The issue of uncertainty is not new in this field; however, it has gradually become a central theme, particularly in connection with increasing data volumes and availability of mapping platforms for public engagement. The central problem of **big data** is that data volume alone does not guarantee usability. Systematic approaches to data are needed to obtain meaningful information. Working with data quality and uncertainty is key to preventing data-rich analyses from leading to false conclusions (Goodchild, 2009). This work, with its emphasis on user approach, shows that even in the big data environment, the key question remains: who interprets the data and with what knowledge.

Following current developments, data-driven modeling in geoinformatics brings **new possibilities** but simultaneously emphasizes the **crucial role of working with uncertainty and data quality**. As Koldasbayeva et al. (Koldasbayeva et al., 2024) show, environmental applications face fundamental challenges related to input data heterogeneity, spatial autocorrelation, and insufficient model validation. Without systematic resolution of these issues, even sophisticated approaches based on big data and machine learning can lead to misleading conclusions. This finding directly supports the user-centered approach of this habilitation thesis, which emphasizes that meaningful use of big data is possible only when uncertainty is an integral part of the analytical process from the beginning. As Zou, Song, and Cervone (Zou et al., 2024) show, big data development brings not only new opportunities but also fundamental methodological challenges. They point out that data volume and availability alone do not guarantee usability if issues of heterogeneity, autocorrelation, and uncertainty are not systematically addressed. Current method reviews confirm that combining different data sources—from remote sensing through sensor networks to participatory collection—places new demands on validation and result interpretation.

The results also build on research in **uncertainty visualization** (MacEachren et al., 2005), which connects insights from cognitive sciences, data analytics, and cartography. The finding that subjective user preferences often do not match the objective effectiveness of visualization methods (Brus et al., 2019) brings a new empirical argument to the international debate and confirms that uncertainty visualization is not just a matter of graphic form but also of education and user guidance. The importance of uncertainty visualization lies not only in aesthetics or technical map rendering, but also directly affects users' cognitive load and thus their decision quality. As confirmed by (Chakraborty et al., 2024), different visualization methods can lead to different decision-making efficiency. Intuitive graphic forms can reduce error rates and speed up decision-making, while overly complex or incomprehensible methods can burden users. Findings also confirm that visualization effectiveness depends on individual user experience and abilities. This insight shows that the core of the presented framework is comprehensive work with uncertainty—from modeling and visualization to its practical impacts on decision-making.

As Goodchild and Li (Goodchild & Li, 2012) or Senaratne et al. (Senaratne et al., 2017) point out, **participatory approaches**, whether in the form of VGI or citizen science, bring significant value only when quality and uncertainty issues are systematically addressed from the beginning. This conclusion is confirmed by empirical studies (Balázs et al., 2021; Kosmala et al., 2016; Stankiewicz et al., 2023), which show that even very extensive databases can be sources of bias rather than reliable foundations for decision-making without adequate mechanisms. This is directly evident in cases such as monitoring bee colonies within the COLOSS association (Brodschneider et al., 2019; Brodschneider et al., 2022) or monitoring calamitous mosquito species, where data quality and validation form essential prerequisites for their usability in environmental management.

Working with uncertainty and data quality is also crucial in the context of **creating maps for users with visual impairments**. As Lobben and Lawrence (Lobben & Lawrence, 2012) or Rowell and Ongar (Rowell & Ongar, 2003) show, data density and detail alone can be more of an obstacle than benefit without adequate generalization and content hierarchization. Map quality is therefore not evaluated by the number of displayed elements but by their comprehensibility and relevance for the target group. Adding multimodal elements, especially audio content (Brock & Jouffrais, 2015; Giudice et al., 2012), shows that even extensive data can be made accessible only when issues of form, interpretation, and interaction are systematically addressed from the beginning. This insight underscores the general thesis that quality and uncertainty are not just technical data attributes but fundamentally affect their usability in specific user scenarios. These examples clearly show that the methodological framework is not limited to environmental studies but has general validity throughout geoinformatics.

Extension to Other Geoinformatics Areas

Although examples in this work were primarily anchored in selected environmental studies, the proposed **methodological framework** has broader reach and **can be applied in other geoinformatics areas**. One is climate change modeling, where work involves numerous scenarios and predictions characterized by high uncertainty. The user-centered approach can contribute to better understanding of results not only by the scientific

community but also by municipalities and public administration. It shows that when differences between scenarios are not clearly communicated, even quality models are often misinterpreted. In line with mentioned results, research in climate uncertainty communication confirms that presentation methods fundamentally affect target group behavior and decision-making. Daron (Daron et al., 2015) proves that visual style and graph detail level significantly affect how users interpret climate data. The fundamental application level is then the communication of scenarios, often presented in the media without proper explanation. The study by Painter et al. (Painter et al., 2024) points out that media often simplify created scenarios, again leading to misinterpretation.

Similarly with **hydrological and flood modeling**, where flood zone maps and probabilistic scenarios are commonly used. These outputs are methodologically precise but their comprehensibility for users is often limited. An approach systematically reflecting cognitive limits and target group needs could fundamentally increase their practical usability in crisis management and long-term planning. An equally current area is **remote sensing and machine learning**, which today produce enormous amounts of classifications and predictions (e.g., land use, object detection). These models always carry error, but results are often presented without explicit information about their reliability. Experience from this work shows that visualization and communication of uncertainty can be a way to increase use of these data in practice (Liu et al., 2004; Ma et al., 2020).

Data Quality and Standardization

From the perspective of working with uncertainty, not all proposed solutions are correct, and simply adding information about uncertainty and data quality can raise **questions about their credibility among users**. Due to enormous data volumes, standardization is essential in geoinformatics, and individual data quality standards should be consistently followed (Fischer et al., 2023; Gupta & McArdle, 2024). However, this requirement faces the reality that many environmental studies do not include a geoinformatician on the team who could control the process and methodically oversee individual steps. If data quality is not defined and systematically addressed from the beginning, it is nearly impossible to create visualizations that effectively work with this information (Wagner & Henzen, 2022). This leads to a methodological impasse demonstrated in many studies. A possible way out may be broader education of scientists, better communication about the need to describe data quality, striving for maximum transparency in collection and processing, and not least demonstrating positive impact on decision-making processes. Thorough description of used models and analyses improves communication possibilities and allows users to develop critical views of outputs even from studies with quality input data.

Practical Experience and the Concept of Representativeness

During my professional career, I have repeatedly had the opportunity to address data quality and uncertainty issues with many experts at conferences, research stays, or projects. One of the most significant experiences is that even when methodological procedures and approaches exist, their **transfer to practice** is not always simple and straightforward. A clear example can be demonstrated with the COLOSS association and the colony loss monitoring group. After extensive discussions and initial attempts to objectify loss reporting across individual countries, result publication was supplemented with a rule requiring not only the loss value itself but also information about the number of beekeepers, proportion of the total, and number of colonies the value concerns. Comparing Germany with ten thousand respondents to Slovenia with several hundred respondents through a single relative value without additional context distorted reality in early presentations. Only after nearly a decade of effort have recent years shown that the community has begun approaching data quality reporting more responsibly, and the author's proposed approach to presenting representativeness has become used not only in the Czech Republic but also in Italy, allowing more objective presentation of colony data. However, this procedure cannot always be applied as it requires mandatory colony registration, which most countries do not require from beekeepers. Analogous conclusions apply to botanical and occurrence data. This area also confirms that careful data cleaning and removal of erroneous records brings substantially better results and advances research toward more objective results. From the author's perspective, data quality standardization should be performed at least at the basic metadata description level for all studies using spatial data.

Citizen Science and Data Quality from Public Collection

For the author's scientific work and many other domains, the quality of **data obtained through participatory collection is crucial**. It shows that choosing the right questions in questionnaire design can improve the quality of the data obtained. A clear example is the question about the length of beekeeping experience and operation size. Based on these two indicators, some responses can be weighted by experience and given greater emphasis. This proved crucial, for example, in the subsequent parameterization of landscape suitability models for apiary placement. Similar approaches can be applied to respondent residence and local environmental knowledge. Responses from respondents who regularly move through the given environment and possess local expertise have significantly higher informative value. In studies focused on calamitous mosquito species, distinguishing between territory residents and visitors brought noticeable data quality improvement (Rypl et al., 2024). This division subsequently allowed results to be interpreted with greater precision and objectification.

Work Limitations

Although the work demonstrated robustness and broad applicability, its limits must be **critically reflected**. From a broader perspective, the work's strength is the methodology's applicability across many areas. The work successfully combined various approaches, allowing for certain generalization of findings. However, it must be emphasized that most case studies were conducted in Europe, so cultural and locally specific differences must be considered when applying them in other regions. The presented examples come primarily from environmental studies, specifically beekeeping, invasive species protection, and participatory projects. However, this selection does not limit result relevance—rather, it shows that principles of working with uncertainty are applicable across fields. From a methodological perspective, whether data comes from citizen science, occurrence databases, or model outputs is not decisive; the key is the ability to transparently describe uncertainty sources, adapt their presentation to target users, and evaluate practical impact.

Another challenge is the so-called **uncertainty paradox**: while proper work with uncertainty leads to better decisions, many studies show that in practice, too much information can discourage users (Calvo et al., 2022; Korporaal et al., 2020). Many studies show that reality is more complex and users often do not understand uncertainty or ignore it in decision-making if not presented comprehensibly (Courteille et al., 2025; Schneider et al., 2022). Overly complex visualization can increase cognitive load and paradoxically reduce decision quality. This opens a fundamental question: ***where lies the optimal boundary between information completeness and comprehensibility?*** This habilitation thesis shows that the answer lies in thorough user testing and adapting methods to specific target groups. The phenomenon of cognitive limits when working with uncertainty will be very difficult to generalize and requires deeper research in specific application domains. Work with uncertainty, thus cannot be reduced to the volume of provided information, but must include testing the cognitive limits of specific target groups.

Another limitation is the question of scalability and the real implementation of the proposed tools. The presented prototypes—whether for decision support in beekeeping, illegal dump management, or haptic map creation—proved very useful. However, the transition from functional prototypes to widespread deployment is a fundamental challenge exceeding basic research scope. It requires not only technical solutions but primarily building trust between end users and institutions. Implementing work with uncertainty is indeed time and organizationally demanding and encounters human and financial resource limits in many applications. However, results of studies presented here show that with appropriate user involvement and targeted methodological preparation, significant advances can be achieved—whether in objectifying results (COLOSS), refining models (mosquito abundance data), or presenting data to users with specific needs.

Despite the mentioned limitations, the work has broad impact. It confirms that in the era of 'big data,' the geoinformatician's role shifts from analyst or mapmaker to **methodological guarantor** who helps other scientists from different fields **critically and correctly work with spatial data**. The systematic approach to uncertainty developed here provides a foundation for future developments in the field, which are detailed in the concluding chapter.

CONCLUSIONS AND FUTURE WORK *Chapter 7*

The thesis presents a **comprehensive, repeatedly validated, and practically applicable methodological approach for addressing uncertainty and data quality in environmental geoinformatics**. It also tackles a fundamental challenge in environmental geoinformatics: systematically working with uncertainty and data quality to enhance rather than hinder scientific understanding and practical decision-making. Through four interconnected research questions, the work developed, tested, and applied a comprehensive user-centered approach that bridges the gap between technical data processing and effective communication.

Answering the Research Questions

RQ1 – How can uncertainty in environmental data be conceptualized from a user-centered perspective? Chapter 2 introduced a paradigm shift in how we approach uncertainty. Rather than viewing it as a technical problem to be minimized, we reconceptualized it as a communication challenge requiring cognitive and social considerations. The user-centered framework developed here inverts traditional workflows. Instead of starting with data and ending with users, we begin with user needs and work backward to determine appropriate data handling and visualization strategies. The key finding is that uncertainty is not an absolute property of data but a relative concept dependent on user context, expertise, and decision-making needs. This insight has profound implications for designing geographic information systems and environmental decision support tools. The framework's three pillars—refined terminology distinguishing data quality from uncertainty, the concept of "fitness for use," and a structured decision process—provide practical guidance for practitioners. Annual validation through teaching has confirmed that even advanced students struggle with these concepts when approached traditionally yet grasp them readily through the user-centered lens.

RQ2 – What are the sources of uncertainty in heterogeneous data types and how can they be methodologically addressed? Chapter 3 demonstrated the framework's versatility across three distinct uncertainty scenarios, each representing common challenges in environmental science. Expert interpretation uncertainty, exemplified by land cover classification in post-mining landscapes, revealed how subjective judgment—often hidden in final products—can be systematically captured and communicated. The innovation here was transforming unquantifiable expert confidence into structured attributes that could be analyzed and visualized. Citizen science uncertainty, explored through mosquito monitoring in PLA Litovelské Pomoraví, showed how subjective perceptions from many participants could be transformed into reliable decision support through spatial aggregation, integration with objective data layers, and validation against expert observations. Despite inherent uncertainties, this work proved that participatory data could provide unique insights unavailable through traditional monitoring. Interdisciplinary integration uncertainty, addressed in crop wild relatives (CWRs) research, tackled the compound challenges of semantic vagueness (what constitutes "marginal environments"), positional inaccuracy in occurrence records, and scale mismatches between different data sources. The methodological contribution here was developing workflows that explicitly account for multiple uncertainty types simultaneously, using techniques like adaptive buffering based on coordinate quality. These cases collectively demonstrate that no single approach fits all uncertainty types. Instead, we need a toolkit of methods tailored to specific data sources and contexts, unified by the common principle of transparency and user focus.

RQ3 – How can we design and validate visualization methods that effectively communicate uncertainty to end users? Chapter 4 bridged the gap between theoretical frameworks and practical implementation through two complementary approaches. Applying fuzzy boundary visualization in biogeography demonstrated how uncertainty-aware cartography can enhance scientific communication in disciplines where such methods were previously mostly uncommon. By replacing sharp distribution boundaries with gradients reflecting occurrence probability, these maps better represent ecological reality while remaining interpretable to domain experts. The empirical validation study using eye-tracking technology revealed a critical disconnect between what users

think works and what actually works. Participants consistently preferred certain visualization methods (like blur effects) in surveys yet performed worse with these methods in practical tasks. Conversely, less-preferred methods (like color saturation) proved more effective for decision-making. This finding challenges decades of visualization practice based primarily on aesthetic preferences and expert opinion. The study also confirmed that integrated uncertainty visualization—where uncertainty is encoded directly in map symbols rather than shown as separate layers—reduces cognitive load and improves interpretation accuracy. The finding that experts and novices showed similar viewing patterns suggests that good uncertainty visualization can level the playing field, making complex environmental data more democratically accessible.

RQ4 – How can systematic work with uncertainty support practical tools and decision-making in environmental and societal contexts? Chapter 5 demonstrated real-world impact across multiple scales and domains. In international beekeeping management, the work with COLOSS questionnaires showed how acknowledging sampling uncertainty through representativeness metrics transforms raw survey data into reliable policy guidance. Developing decision trees for *Varroa destructor* management strategies, explicitly accounting for regional variations and beekeeper typologies, provides actionable recommendations that have reduced colony losses. For invasive species management, combining citizen observations with species distribution modeling produced predictive maps that now guide monitoring efforts by Czech conservation authorities. The development of TouchIt3D technology for haptic maps represents the ultimate expression of user-centered design, making spatial information accessible to visually impaired users. Here, uncertainty takes new forms—generalization uncertainty from simplifying visual details for tactile perception, semantic uncertainty in material-meaning mappings, and cognitive uncertainty about user interpretation. The multisensory approach, combining touch with audio feedback, demonstrates how uncertainty can be addressed through redundancy and user adaptation.

Synthesis and Broader Implications

The thesis demonstrates that uncertainty is not merely a technical nuisance but a fundamental aspect of environmental data that, when properly addressed, enriches rather than diminishes scientific value. The user-centered approach provides a robust framework for transforming uncertainty from a hidden weakness into transparent information that supports better decision-making. Several cross-cutting insights emerge from this work: Uncertainty as information, not noise. Traditional approaches treat uncertainty as error to be minimized. This thesis shows that uncertainty carries valuable information about data limitations, collection contexts, and appropriate use cases. Making uncertainty visible helps users calibrate their confidence and make more informed decisions. Counter-intuitively, acknowledging complexity through uncertainty visualization often leads to simpler, more honest communication than presenting falsely precise information (**the paradox of simplicity**). Users consistently understand and trust transparent presentations of limitations more than artificially certain outputs. Good uncertainty visualization reduces the expertise gap, making complex environmental data accessible to broader audiences. This has profound implications for participatory environmental management and citizen science initiatives, illustrating a broader democratization through design. While developed for environmental applications, the framework presented applies to any domain where experts create data under pressure—from medical imaging to financial modeling to climate projections. User focus, transparent uncertainty, and empirical validation principles are universally relevant.

Future Research Directions

Building on the findings of this thesis, future research will focus on four key areas:

1. **Development of intelligent geoparticipatory systems:** Future research will aim to develop applications for participatory data collection that will use various techniques, including artificial intelligence in the field, to validate entered information and verify data plausibility or validity. This direction builds on existing experience with the illegal dump reporting application and implemented procedures in online questionnaires, where cross-tabulations or conditional field filling were used to increase data quality. However, future systems will go further: artificial intelligence will enable imme-

diate verification of consistency and credibility of entered data, analyze visual material (e.g., counting larvae in dishes or automatic object detection in the field), thereby significantly increasing precision and efficiency of participatory data collection.

2. **Expansion of multisensory communication and uncertainty reduction:** Future research will focus on expanding work with haptic maps toward multisensory communication. Besides visual display, this will involve using new 3D printers with various materials, haptic gloves for detailed feedback, and adding audio layers. Artificial intelligence also has great potential—it could generate content directly on haptic maps based on user verbal input. Connecting visual, haptic, and auditory elements would allow users to better understand spatial data and perceive uncertainty in ways that meet their needs.

3. **Design of new software tools for working with uncertainty:** The third area will be developing software tools that enable presenting data, including information about their uncertainty and quality. Research will build on data obtained from beekeepers, displaying it in new forms where reliability indicators are part of the output. In follow-up projects funded by the Ministry of Environment, we plan to create decision support tools for beekeeping that connect spatial data with climate information and model results. Displaying certainty and uncertainty levels of these models will be a natural part of the application and help users better understand results and make decisions based on them.

4. **Integration of approaches into education and practice:** The fourth area will be incorporating approaches to working with uncertainty directly into university teaching and professional training. Currently, this issue is partially covered in my taught course **Spatial Modeling**, but additional space is offered especially in courses **Digital Elevation Models** or **3D Technologies**. The goal is for work with uncertainty to become a natural part of teaching and for students to master its application in various geoinformatics areas.

Final Thoughts

The journey from **recognizing uncertainty as a problem to embracing** it as an essential component of scientific communication represents a fundamental shift in how we approach environmental data. This thesis provides both a **theoretical foundation and practical tools** for this transformation. By placing users at the center of our considerations, we transform uncertainty from a barrier into a bridge—connecting data producers with decision-makers, science with society, and current understanding with future discoveries. The ultimate measure of this research is not the number of papers or methods, but better environmental decisions—made because uncertainty was acknowledged rather than hidden, communicated rather than ignored, and understood rather than feared.

In an era of rapid environmental change and increasing data complexity, such transparent, user-centered approaches to uncertainty are valuable and essential for navigating the challenges ahead. As our data-rich world grows more complex, bridging the gap between sophisticated analyses and user needs becomes not just an academic challenge but a prerequisite for responsible environmental decisions.

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APPENDICES

Appendix 1: The User Centered Framework for Visualization of Spatial Data Quality

Brus, J., & Pechanec, V. (2015). The User Centered Framework for Visualization of Spatial Data Quality. In J. Brus, A. Vondrakova, & V. Vozenilek (Eds.), *Modern Trends in Cartography: Selected Papers of CARTOCON 2014* (pp. 325–338). Springer International Publishing. https://doi.org/10.1007/978-3-319-07926-4_25

Appendix 2: Depiction of uncertainty in the visually interpreted land cover data

Brus, J., Pechanec, V., & Machar, I. (2018). Depiction of uncertainty in the visually interpreted land cover data. *Ecological Informatics*, 47, 10–13. https://doi.org/10.1016/j.ecoinf.2017.10.015

Appendix 3: Geoparticipation as a tool for mapping calamities mosquito hotspots: A casestudy from Litovelské Pomoraví, Czechia

Rypl, O., Burian, J., Pánek, J., & Brus, J. (2024). Geoparticipation as a tool for mapping calamities mosquito hotspots: A case study from Litovelske Pomoravi, Czechia. *Environmental and Sustainability Indicators*, 24. https://doi.org/10.1016/j.indic.2024.100509

Appendix 4: How Could the Use of Crop Wild Relatives in Breeding Increase the Adaptation of Crops to Marginal Environments?

Renzi, J. P., Coyne, C. J., Berger, J., von Wettberg, E., Nelson, M., Ureta, S., Hernández, F., Smykal, P., & Brus, J. (2022). How could the use of crop wild relatives in breeding increase the adaptation of crops to marginal environments? (vol 13, 886162, 2022). *Frontiers in Plant Science*, 13. https://doi.org/10.3389/fpls.2022.1101822

Appendix 5: Click beetle larvae from Cretaceous Burmese amber represent an ancient Gondwanan lineage

Kundrata, R., Rosa, S. P., Triskova, K., Packova, G., Hoffmannova, J., & Brus, J. (2025). Click beetle larvae from Cretaceous Burmese amber represent an ancient Gondwanan lineage. *Scientific Reports*, 15(1). https://doi.org/10.1038/s41598-024-80950-w

Appendix 6: Intuitiveness of geospatial uncertainty visualizations: a user study on point symbols

Brus, J., Kucera, M., & Popelka, S. (2019). Intuitiveness of geospatial uncertainty visualizations: a user study on point symbols. *Geografie*, 124(2), 163–185. https://doi.org/DOI 10.37040/geografie2019124020163

Appendix 7: Comparison of apiculture and winter mortality of honey bee colonies (Apis mellifera) in Austria and Czechia

Brodschneider, R., Brus, J., & Danihlik, J. (2019). Comparison of apiculture and winter mortality of honey bee colonies (Apis mellifera) in Austria and Czechia. *Agriculture Ecosystems & Environment*, 274, 24–32. https://doi.org/10.1016/j.agee.2019.01.002

Appendix 8: Varroa control strategies of different beekeeper groups and corresponding honey bee colony mortality in Central Europe

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Appendix 9: Design of decision support tools for the quality assessment of illegal dumping notifications based on crowd-sourced data

Brus, J., Vrkoč, J., & Kubásek, M. (2016). Design of decision support tools for the quality assessment of illegal dumping notifications based on crowd-sourced data. *Environmental Modelling and Software for Supporting a Sustainable Future,* Proceedings 8th International Congress on Environmental Modelling and Software, iEMSs 2016, Toulose.

Appendix 10: Efficient Interactive Tactile Maps: A Semi-Automated Workflow Using the TouchIt3D Technology and OpenStreetMap Data

Barvir, R., Vondrakova, A., & Brus, J. (2021). Efficient Interactive Tactile Maps: A Semi-Automated Workflow Using the TouchIt3D Technology and OpenStreetMap Data. *ISPRS International Journal of Geo-Information*, 10(8). https://doi.org/10.3390/ijgi10080505

Appendix 11: Creating a Haptic 3D Model of Wenceslas Hill in Olomouc

Lazna, R., Barvir, R., Vondrakova, A., & Brus, J. (2022). Creating a Haptic 3D Model of Wenceslas Hill in Olomouc. *Applied Sciences-Basel*, 12(21). https://doi.org/10.3390/app122110817

APPENDIX 1

The User Centered Framework for Visualization of Spatial Data Quality

Brus, J., & Pechanec, V. (2015). The User Centered Framework for Visualization of Spatial Data Quality. In J. Brus, A. Vondrakova, & V. Vozenilek (Eds.), *Modern Trends in Cartography: Selected Papers of CARTOCON 2014* (pp. 325–338). Springer International Publishing. https://doi.org/10.1007/978-3-319-07926-4_25

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The User Centered Framework for Visualization of Spatial Data Quality

Jan Brus and Vilém Pechanec

Visualization of uncertainty of spatial data includes a wide range of issues relating to data quality of the individual components, their definition, nature, database design, graphic methods, selection and implementation, dynamic monitoring and description of the error propagation in GIS operations, and many more. It follows that it is necessary to explore, extend and integrate existing research in uncertainty visualization of spatial data. The notion of uncertainty is defined the first part of paper, there is also described the issue of data quality as a variable which is used for visualization of uncertainty in spatial data. The principals of uncertainty visualization are discussed further more with emphasis on basic theories that have major impact on shaping the contemporary concept of uncertainty visualization. The attention is focused primarily on issues related to communication models, cognition, perception and semiotics. It is emphasized the need to perform research not only in particular visualizations, but also to carry out research which develops specific frameworks and concepts of visualization of spatial data quality. Proposed frameworks should incorporate users as a key factor which influences whole visualization. In this study the widen user centered framework of uncertainty visualization is proposed. This framework is based on results from user centered research on uncertainty visualization and on the basis of obtained findings and results from testing. This framework is able to reflect the various hierarchical natures of spatial data and integrate the various parameters of quality of spatial data as a basis for visualization.

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Uncertainty

The notion *uncertainty* is mentioned quite often in both foreign and Czech literature and in the last twenty years has become the subject of focus of more and more professionals. The current development of technology only supports this fact. In the field of geoinformatics, the situation is no different, quite to the contrary. Quick development of implementations of individual theories working with this approach makes uncertainty an integral part of most operations with spatial data. Despite the stated fact, understanding uncertainty in the field of geoinformatics is still limited by problematic definition of this notion in individual science disciplines.

In literature, there are quite a few definitions of uncertainty. Great number of definitions reflects the complexity of the issue hidden under this general phenomenon. For instance, the difference between *accuracy* and *uncertainty* is debated very often. In cartography, the two terms are understood as very similar, and sometimes, they are even considered to be synonyms (Boukhelifa and Duke 2007). In connection with uncertainty, we can talk about accuracy, reliability, clearness, distinctiveness, etc. (Duckham et al. 2001). More generally, uncertainty can be defined as imperfection of the users' knowledge concerning data, processes or results. Thus, *uncertainty* is a multi-faceted notion including many types. They include inaccuracy, indeterminacy, imperfect knowledge, inconsistency, missing information, buzz, ambiguity, lack of reliability, doubt and others. Definitions of uncertainty are thus very rich and reflect its various properties. Thanks to numerous types of uncertainty, there is no clear agreement in the used terminology or a generally accepted meaning (MacEachren et al. 2005). The ambiguity of translation from various languages, in particular from English, has a distinctive impact on this situation too, and moreover, every scientific discipline operating with uncertainty, uses different terminology. Even professional literature states notions like uncertainty, indeterminacy, haziness, generality, bilinguality and others often as synonyms. From this view, the effort to follow authoritative foreign sources is surely praiseworthy, however, it is important to take into account also various specifics of the environment (professional, territorial, linguistic) in which these authorities formulate their standpoints (Kalouda 2010). To define and use individual terms correctly in geoinformatics, it is necessary to know how to work with the notions. The main aim of the paper is to discuss and suggest user centered framework for spatial data quality visualisations. In the first part of the paper is described spatial data quality, then continuously mention visualisation issues. Finally all aspect of new framework are discussed and described with min aim to facilitate the whole process.

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Data Quality

This part deals with the quality of spatial data as a variable used to visualize uncertainty in spatial data. Therefore, in the beginning of this chapter, we must define notions and mutual relationships that are used in the text and thus illustrate problematic and ambiguous view of data and information with geographic or spatial aspects. The definition of the notion spatial data itself is difficult, and there are often problems with terminology and correct understanding of the meaning of this expression. In practice, there is not only this notion, but a whole spectrum of notions bearing similar and often confused meaning.

To determine and define the quality of spatial data, the actual meaning of the word *quality* must be understood. Moreover, the notion quality must be used with great discretion, because the notions uncertainty and quality of spatial data are not synonyms, although, in many cases, they are very close to each other. They have similar categories, deal with similar domains and in many cases, quality is confused with uncertainty and vice versa (Brus et al. 2013). Uncertainty in this meaning is considered a property allowing to evaluate how good (of what quality) are the available data, and uncertainty distinctively influences the quality of spatial data. Basic and distinctive difference is the fact that uncertainty can be introduced in any phase of the production of mapping data and GIS analyses (monitoring, conceptual modelling, measuring, analysis, visualization etc.) including perception by the end users, and as such, it concerns not only the quality of the spatial data, but the whole process of transferring geographic information.

The notion of quality and its contents has been undergoing historical development and transformation. From this point of view, it must be deciphered not only as part of the given context and discourse of the scientific field, but also with regard to its genetic and semantic interpretation. Thus, quality in the meaning of this paper can be most conveniently defined as each property or quality that belongs to something, or is connected to something, as the thing that modifies the thing to fulfil its purpose for which it was created or founded (Brugger 1994), and quality means the quality of the acquired information. From this point of view, a high-quality piece of information can be considered such piece of information that is useful and helpful for its "consumer", which, in connection with traditional definition of information means that the information quality is very dependant not only on basic data, but on the users themselves. High-quality information can then be defined as "accurate, trustworthy and sufficient for the decision-making of the user". In connection with the possibility to interpret data and information in many ways, also above-mentioned knowledge (tacit, explicit) and experience of the originator and recipient of the information enter the process. Therefore, it is very interesting to consider also the efficient quality of information—actual usefulness where an important factor is the skills of the information user. For users without sufficient skills, information is not of high-quality (useful), but, quite to the contrary, the quality of the presented information can even decrease. This fact is also reflected by the used definition of quality "convenience of use" (Beard

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et al. 1991; Chrisman 1984; Hunter 1999). In industrial sense, quality is basically the level of fulfilment of the production process, it is i.e. a function of non-substantial qualities such as completeness and consistency influenced by production process (Veregin 1998). Based on the definition of quality derived from encyclopaedic dictionary (Weber and Buttenfield 1993), quality is viewed as a distinguishing property allowing to distinguish whether the given property has positive or negative character. Based on this division, two other terms can be derived—accuracy and mistake. If quality has a positive character, it could be measured by the likeliness to the chosen model or reality, and the result is the already mentioned term accuracy. On the other hand, negative approach is measured by discrepancy, i.e. mistake. From the point of view of geoinformatics, there is a number of other views at the definition of quality of spatial data, because quality is always related to a range of data characteristics. Individual definitions thus usually reflect various views of the terminology of the notion itself and differ from author to author.

From the beginning of the development of quality of spatial data, this field has been a key subdiscipline of geoinformatics. It is considered to be of great importance both in the field of academic workplaces and in governmental and industrial organizations. The quality of spatial data has been the topic of many conferences and seminars and international activities (e.g. AGILE, GEOIDE, NCGIA and others). However, the whole discipline, with regard to uncertainty, deals with the above-mentioned problem, i.e. the disunion of used definitions and inaccurate terminology. The stated can be demonstrated by an example where representatives of governmental institutions and scientists working in academic environment are asked to define "data quality" and "uncertainty". It is very likely, that differing and ambiguous answers will be given. The problem lies in the community of people dealing with the quality of spatial data and uncertainty. In scientific articles, professional reports and studies, it is very problematic to identify various concepts that are called the same, or same concepts bearing differing names. As stated in the preceding chapters, notions like uncertainty, mistake, accuracy, ambiguity and their interpretation always reflect the scientific field from which the author using the terminology is coming from. From the point of view of quality and uncertainty of spatial data, in this interpretation, a division into two different communities of people dealing primarily only with quality or uncertainty can be traced. Each of these groups goes to their "own" conferences such as International Symposium on Spatial Data Quality or International Symposium on Spatial Accuracy Assessment in Natural Resources and Environmental Sciences. However, information and opinions are usually not interchanged between these two groups (Devillers et al. 2010).

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Visualization of Data Quality

Recently, requests to visualize data quality occur more and more often. This fact was distinctively influenced by the acceptance of uncertainty as an important part of data (Schneiderman and Pang 2005). Despite the researching efforts in this field, there is still no defined way to visualize uncertainty making this activity user-friendly for wider group of users. Traditionally, information about uncertainty is visualized using very limited methods and to acquire final result, combination of various software is necessary. To find convenient methods and implement them, user testing of created representations must be still performed. In general, research in the field of spatial data visualization is primarily based on the definition of uncertainty itself, development of methods for graphic depicting of the information, creation of connections between spatial parts of data quality and visualization methods. User evaluation of thus created visualization is what matters, and still there are many questions concerning the impact of the use of specific types of visual representations on decision-making process to be answered.

Cognitive Aspects of Spatial Data Quality Visualization

As stated by Weick (2001), regardless of the field, it is necessary to take into account rather the perception of a specific individual than objective reality. This approach will allow easier understanding of uncertainty and related analyses, modelling and other aspects connected to this issue. In this part of the chapter, we are going to focus in particular on human factors influencing visualization of uncertainty and data quality.

In compliance with this approach, we can talk about cognitive cartography. The history of cognitive research in the field of geography and cartography can be traced back to the 1960s. With the beginning of occurrence and definition of the notion GIScience (Goodchild 1992), cognitive research was applied also as part of this discipline (Montello 2009). Cognitive cartography represents a research field that uses concepts and procedures of cognitive psychology to uncover mental representations and images with the objective to evaluate those images and to acquire geographic information from individual users (Blades and Spencer 1987). As part of this approach, human psyche is viewed as information processing system. Unlike computing approach which rather works with cartographic tradition, cognitive approach emphasizes in particular the user. The objective is to provide visualizations that work in compliance with what is known about human perception and cognition of geographic space and its visual representations (Fabrikant and Buttenfield 2001; Fabrikant 2001).

Leading professional in the field of cognitive cartography Montello (2002) said that the research performed in this field is an approach that can, thanks to technological progress, help to develop cartography as a whole. In his conception,

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cognition includes inner mental structures and processes that are part of perception, attention, thinking, consideration, learning, memory and linguistic and nonverbal communication, when cognitive cartography itself includes the application of cognitive theories and methods to understand and read maps, mapping and using the map to understand cognition. Cognition includes perception, learning, memory, thinking and solving problems including communications. It also includes external symbolic structures and processes, for instance maps and written instructions to perform formal spatial analyses that help internal recognition (Montello et al. 2004; Montello 1998). From the perspective of cognitive science, as part of information science, which, according to Peuquet (2002) also includes cartography, sensual constructions of individual situations are created by an individual, i.e. an individual is an active agent. From this point of view, an individual is also active in interaction between information structures and own conceptual framework. In the case of cognitive cartography, this interaction is performed between representations of models of geographic information such as maps, and saved knowledge structure of the user. This interaction allows the individual to perform individual adjustments or changes of their knowledge, because a piece of information acquired from the surrounding environment is the element that creates the knowledge itself. We should distinguish between cognition as a process and cognition as a result of this process, i.e. findings and knowledge. Basic approaches to explain cognition are symbolic representation, connectionism and semiotic approach.

Perception becomes an important element of visualization of uncertainty. Perception is an internal feeling created from an impression to our senses, accepting impressions or feelings using one of our senses. It is important to realize that human senses are not perfect and can thus distort reality. In other words, we can observe that perception itself provides more or less imperfect view of reality (Mezias and Starbuck 2003). Some professionals are of the opinion that human personality influences perception of individuals in particular. Others (Fiske and Taylor 2008) are of the opinion that properties that influence perception the most include clarity, legibility and clearness of the grounds. Here, it is convenient to state that each cartographic work can be viewed in three different ways: from the professional (contents of the map), technical (cartographic interpretation of the map contents, print, font, quality of work) and aesthetical (map composition, used colours, etc.) points of view (Voženílek 2004). From the point of view of uncertainty visualization, it can be observed that even though all stated parameters and variables have minimum impact on the correct transfer of information, none of the possibilities can be excluded (or declared insubstantial) for deeper understanding of this issue. By defining uncertainty across the spectrum of fields, other interesting facts that are more or less, directly or indirectly connected to depicting of uncertainty and subjective perception in maps were ascertained. As Bourgeois (1985) described, perception of individuals can differ distinctively, which leads to the perception of relativity.

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User-Centered Framework for Uncertainty Visualisation

The preceding chapters summarized individual findings concerning great amount of individual aspects that can have distinctive influence over the visualization of uncertainty. Visualization of uncertainty is, from this point of view, a discipline lying at the borders of a number of different scientific fields. As a completely starting point during study of uncertainty can be considered the properties of uncertainty lying in the basis of natural processes and it is very difficult to describe them. Subsequently, all spatial data acquired from real environment can be analogically affected by a certain form of uncertainty. From the visualization point of view, it is very difficult to visually represent data in a form reflecting their true nature. Moreover from the perspective of the paper and proposed framework is necessary to consider also another frameworks in the same domain which have been already proposed. As the most important frameworks can be considered frameworks done by Voženílek and Kaňok (2011), Buttenfield (2000), Davis and Keller (1997) or Aipperspach (2009).

Uncertainty is an integral part of all operations with spatial data, but also part of all results and cartographic representations. From the point of view of the preceding text, uncertainty was understood as, predominantly, quality of spatial data, as a principal and key element influencing a number of other factors. Visualization of uncertainty also influences the whole process of transfer between the originator and recipient of information, because during cartographic communication, many of problems occur. While defining the concept of visualization of uncertainty, it must be stated that there are more concepts of uncertainty and it was not possible for this paper to deal with all of them.

Individual components of spatial data can be researched from the point of view of individual standards and groups of descriptive parameters of data that can be subsequently used for the visualization of uncertainty can be created. Most of those components are described using metadata. Metadata recording of individual components thus plays a principal role in describing uncertainty. These statements on information bearing data concerning the level of quality of the data however, despite all efforts in the GIScience community still do not include descriptions, instructions or at least recommendations how subsequently represent the information concerning the quality of the data. The situation is further complicated by the fact that as part of research in the field of visualization of uncertainty, there are only few works dealing with the complex issue of the visualization of uncertainty from the cartographic point of view. This fact is an initial presumption for designing a concept for decision-making process concerning the visualization of uncertainty with regard to the user. The design of the concept itself is based on decision-making process concerning the selection of expressing tool as part of topical cartography. As an integral part of individual criteria in the decision-making process during the creation of a map, individual aspects of the visualization of uncertainty are subsequently added in order to create a complete concept. The designed concept also includes many findings acquired during solving the project called Intelligent

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System for Interactive Support of the Creation of Topical Maps that was solved at the Department of Computer Science of the Palacký University in Olomouc and as part of which, the issue of decision-making processes and aspects of visualization are studied in detail (Brus et al. 2009, 2010; Dobešová and Brus 2011).

During creation of a topical map, the initial step is the requirement of the visualization itself, given either by the request of a topical map or only by the need to visualize data for better understanding of the studied data and phenomena. In this moment, the author of visualization must decide the subsequent option and individual steps in the process of the creation of the map. There are usually many options to choose from and there are more variants on which the solution of a specific task can be based. The decision-making process concerning specific properties of the resulting representation is subsequently always influenced in particular by already acquired cartographic skills of the creator of the map and also by the knowledge concerning visualization techniques in general. The primary source of information is therefore study of professional literature. In this phase, a professional should gather and classify all generally available information based on which they will learn the basics, in particular in the given domain, in advance. With regard to the fact that almost 95 % of all map outputs is connected with digital representation of data, the needed knowledge must also include the knowledge of computer graphics and related disciplines. From the point of view of data processing, and subsequent visualization, the ability of the author to work with available software must be also mentioned, since knowledge and availability of technological and software equipment principally influences the whole process of the creation of a map. In many studies, this situation must be emphasized, because of the fact that the rules of optimal process of the creation of a map are often broken and the authors of the final visualization are often domain experts themselves. Cooperation of a domain expert with cartographer is rather unusual. The group of users that visualize and process spatial data using programs for the creation of maps concerning for instance land-use planning, environmental protection and other fields often create the maps intuitively and do not respect cartographic rules. This situation changes the traditional relationship between cartographer and user of the map. Therefore, it is necessary to emphasize initial knowledge of the map creator and consider it as key for the designed concept.

For the designed scheme (Fig. 1), initial step is to determine the objective of the map. The main objective of the map should always be defined before visualization itself and subsequently developed into individual objectives in order to ensure that all objectives will be met. An important factor is, in this case, feasibility of individual objectives and the possibilities to fulfil them. The objectives of visualization including uncertainty should be always evaluated critically in advance in connection to subsequently formulated functions of the occurring visualization. Also, it should be based on already defined methods and already created partial visualizations in order to proceed as is usual for the given topic. However, the used methods should be viewed prudently and critically since many visualization methods were only designed but not tested for user aspects. In general, also

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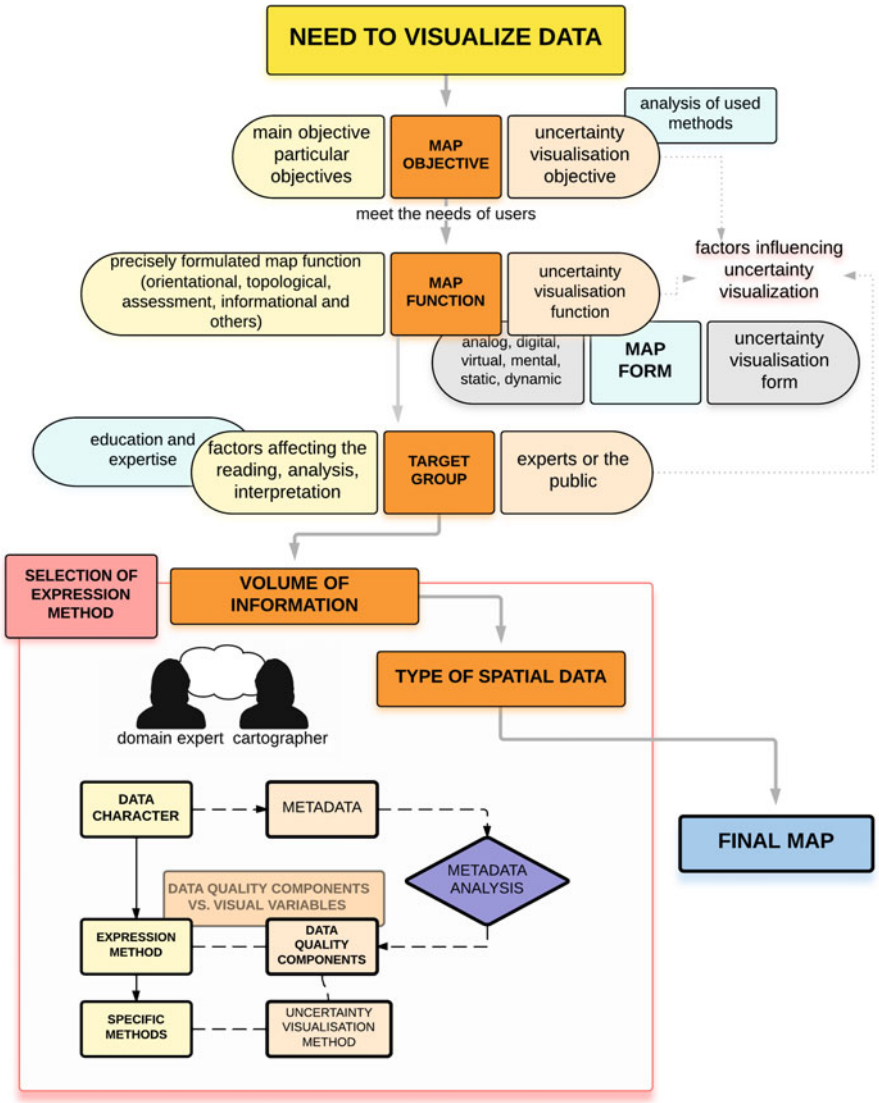


Fig. 1 Proposed framework for user centered spatial data quality visualisation

cartographic rules should be maintained so that visualizations of uncertainty can become a tool that would help to understand reality more comprehensively.

The main contents of the primary and secondary objectives of the map are in particular meeting of the needs of the expected target users of the map. The creator of the visualization who wants to visualize also the quality of spatial data and uncertainty connected to them must realize that individual steps in the process of map reading are influenced by many factors. Communication function of a map

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depends on education, but in particular on the level of professionalism of the map user. User with no knowledge of visualization technologies for visualization of uncertainty works with the map differently than a professional who has been dealing with the issue for some time. This fact was confirmed by executed user testing of designed visualizations of uncertainty executed at the Department of Geoinformatics of the Palacký University in Olomouc, where there were ascertained distinctive differences in the responses of individual respondents (Brus 2013). From the cartographic point of view, it is also important that there is a difference between reading a map that includes uncertainty by a cartographer and reader without cartographic education. A cartographer is able to distinguish fine details and can focus on the technology of the visualization of uncertainty. Most end users of maps including uncertainty are not cartographers from this point of view and therefore, the fact that a cartographer reads the map differently is of no importance during the design of visualization. Map reading is also influenced by age and already mentioned education of the map reader. Scientific maps and visualizations of uncertainty use complex cartographic methods which are commonly used by specialists, however, reading maps with uncertainty requires the user to be well versed in the field. The user is in particular required to be familiar with specific terminology. Terminology is necessary for understanding the studied domain and, in particular, the specific character of the visualization of uncertainty itself. This uncertainty is strongly connected with data and to understand the visualization, the map reader must know these facts. Without the knowledge of terminology, processes and specifications of specific data sets, the designed maps are often illegible for the user. Therefore, the target group of users is key for the selection of the visualization method, its complexity and the level of abstraction needed to understand it.

Despite the issue of visualization users, the designed concept continues by the issue of selection of the most convenient expressive tool. This part is connected with two other criteria that are connected to each other. These are the volume of conveyed information and the kind of spatial data. The stipulation of the level of complexity of the map and the resulting volume of information must be based on the already established principles. Recommendations can be also found in individual perception theories and mentioned principles of the visualization of information. Subsequently, the contents of a map are distinctively influenced by the objective of the map, which then also defines the selection of methods convenient for visualization. The selection of specific methods must be in particular influenced by the primarily depicted reality and by the amount of information that is to be included in the map to fulfil the main objective of the map and from the point of view of the visualization of uncertainty, to fulfil these objectives. The conclusions from this consideration will significantly influence the overall amount of information and therefore also graphical contents of the map. The selection of method for the visualization of uncertainty is then subsequently directly depending upon the selection of cartographic methods for the depiction of a phenomenon. The selection of method is also determined by the criteria of evaluation of the kind of spatial data, which is executed according to the character of the description of properties of

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depicted phenomena. In this phase, the creation of visualization is usually influenced by an expert in the field and by a cartographer. The creator of visualizations must, as part of selection of the most convenient expressive tool acquire quite a few pieces of information from the expert, then analyze it and subsequently decide the specific way of visualization. After the decision, the map including uncertainty is created.

As part of selection of the expressive tools, the following questions can be asked for instance:

- What is the character of the depicted data
- Which components of the quality of data will be visualized?
- Is there a metadata record for the data?
- What are the convenient expressive tools for the visualization of uncertainty?
- To depict uncertainty, which method shall be used: internal or external?
- Which specific methods for the visualization of uncertainty shall be selected?

Acquired expert knowledge is based on the education, gathered experience, intelligence and intuition and communication with an expert. Efficient integration of the mentioned parts leads to the creation of a decision and selection of cartographic expression method for the visualization of uncertainty. Necessary presumption is information on visualized data, in particular metadata description of the data. Based on a detailed analysis of individual components of data quality, it is then necessary to select convenient visual variables and be able to achieve by this integration correct transfer of information concerning the quality of the data using a specific visualization method or combination of methods, bearing the end user in mind as main and key element of the whole concept in mind.

If individual recommendations for the visualization of uncertainty are not maintained, the theory of perception is violated, so mistakes and inaccuracies occur in the map outputs, which leads to incorrect interpretation of not only individual parts, but the whole system of depicted data. From the point of view of the demanding character of the visualization of uncertainty, purposeful and correct map can only be created if three professionals (domain expert, cartographer and geoinformation scientist) or a team of scientists cooperate, which is proven by actual situations when the most elaborate visualizations of uncertainty can be found in project intentions and mutual cooperation between teams of professionals.

The whole process of the visualization of uncertainty can be, based on studying individual key aspects of the visualization of uncertainty, divided into a few basic areas. Uncertainty is created in all parts of the process of cartographic communication and from the point of view of possible elimination, this is an element that cannot be removed. According to the occurrence of uncertainty, we can talk about the uncertainty during the presentation of spatial data due to differing quality of data due to gathering, transformation and other factors. Visualization uncertainty (the uncertainty of visualization) occurs due to a number of factors, when basic processes concern the transfer of information into digital form and subsequent presentation to the end users. Even the users themselves represent a source of uncertainty, because perception is affected by a number of personality and other

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characteristics (Kubíček and Šašinka 2011). It is necessary to emphasize that some factors during the visualization of uncertainty can be removed completely, others can be eliminated partially, and some must be taken as initial and unchanging presumption while designing newly created visualizations.

Discussion

From the point of view of this paper, it is of utmost importance to view the definition of the notion of uncertainty in environmental studies. As was already said in the very beginning of the paper, there is not just one interpretation of uncertainty, different concepts, opinions and definitions can be found. Based on this inconsistency, finding convenient tools and theories that would apply to the whole issue of this scientific discipline is problematic. Due to the complexity of the issue, there is also no unified terminology that would approach the topic globally.

Final and main objective of uncertainty visualizations is to influence the decision-making process of the map reader in way which will help to make more adequate decision based on cartographic symbology. From the point of view of the ability to distinguish individual cartographic signs, the biggest problem and subject of discussion is the lack of software tools for the visualization of uncertainty. Current geographic information systems have almost no implemented tools that can work with uncertainty more comprehensively. It is always only partial functionality of possible ways of visualization. The computing background itself offers program tools, however, only as part of some approaches to modelling of uncertainty. A tool that would allow the user simple and quick display using more methods without the need to convert data between various programs is still missing.

As part of some software, a number of modules and extensions that can work with uncertainty is available, and there is also a considerable number of individual applications, however, these are predominantly the results of research activities, which were not spread extensively or in some cases were not even put into proper operation after testing or termination of financial support. Very often, these tools are specialized for a certain part of the work with uncertainty, so there is no complex solution in this regard. Moreover, these tools are usually not user friendly, and require the user to master deeper theory of work with uncertainty. Therefore, there are rather used as supportive tools, since the user must know where to find them, which again makes their use even more complicated.

From the user point of view, deeper knowledge of the stated issue and also familiarity with GIS products is necessary. Common GIS user is thus not informed by classic software about the uncertainty connected to spatial data. Moreover, the crucial problem with some program environments is cartographic functionality itself, which varies between GIS products considerably. In practice, complicated solutions that prevent spreading between common users must be used. Depicting all aspects of uncertainty in a map is impossible. Basic and limiting elements are cartographic expression tools, limitation of the form of the map and predominantly

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the users of the data themselves. From this point of view, the most important and most critical condition of meaningfulness of visualization is its purpose and in particular the end user.

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APPENDIX 2

Depiction of uncertainty in the visually interpreted land cover data

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Depiction of uncertainty in the visually interpreted land cover data

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A B S T R A C T

Remote sensing data analysis to infer land cover and the subsequent modelling of land use change are subject to uncertainties, which may have an impact on the accuracy of future land-use predictions. Part of these uncertainties come from the visual interpretation of remote sensing data as during this phase a specific knowledge and expertise are crucial. Visual interpretation includes the meaning of the image content but also goes beyond what can be seen on the image to recognize spatial and landscape patterns. The quality of recognition depends on the expertise in image interpretation and visual perception. Based on this statement, it is necessary to visualize also the information about uncertainty. This paper describes different perspectives of uncertainty visualization on the example of visually interpreted aerial photographs in a mining area. The study is focused on visualization techniques for uncertainty awareness analysis of land cover data. This approach should contribute to better understanding, assessment and potential spreading of visual information of uncertainty and help to appraise the data critically. The goal of this paper is to raise uncertainty awareness among practitioners who deal with land cover data and stress the visualizations techniques as a more reliable means to assess the quality, and hence the uncertainty, of these data.

1. Introduction

Land cover and land use data represents the basic data input for a wide range of applications in the environmental field (Ahlqvist et al., 2015; Leyk et al., 2005; Mišijovský et al., 2015; Pechanec et al., 2014). This data can be processed at different spatial and content detail levels, using remote exploration of the Earth (Hunsaker et al., 2013). A very close relationship between the use of the terms land cover (LC) and land use (LU) often leads to confusion of the two concepts. In many maps, LC and LU are often used together: natural and semi-natural areas are described using LC categories, while agricultural and urban parts use LU categories. However, both terms are fundamentally different and they are not interchangeable. An exception may be a situation where the presented material (results of research, statistics, etc.) includes data from both disciplines. LU is therefore the sum of arrangements, activities and inputs which people undertake in a certain type of LC (Jansen and Gregorio, 2002). The analysis of changes in land cover in the context of changing social and environmental conditions makes it possible to evaluate retrospective landscape development, assess influences and estimate development trends, and it is one of the ways to deal with changes in the capacity and ecological stability of the territory. The study is focused on the possibility to visualize uncertainty of visual interpretation on the example of changes in land cover of Heřmanice mining area in the Czech Republic.

2. Problem definition

From the perspective of the studies dealing with land cover, mainly two quantitative quality measures are essential: positional and thematic accuracy (standard 19138, as part of the metadata standard 19115). This definition is questionable in many cases, because an incorrect expression of the LC category may be simultaneously caused by both positional and attribute accuracy; therefore, these data quality components are inseparable. Despite this fact, the above-mentioned division is commonly used in literature, because it presents two completely different domains. Positional accuracy in raster data expresses the degree of the positional certainty of the category represented in a given pixel in relation to the respective relative positions which are considered correct or which are correct. From this perspective, positional accuracy primarily depends on the quality of orthorectification of the satellite or aerial photograph. In vector maps, positional accuracy means the degree of certainty that can be used to consider the position of the boundary between two polygons as correct. As mentioned above, this degree of certainty is inseparable from the attribute accuracy, because the boundary only separates the categories that are defined by classes in the classification scheme used. Therefore, the uncertainty of

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the defined boundary is directly proportional especially to the differences of the given classes, the type of transition between individual classes and the sharpness of the given boundary. The thematic accuracy in raster data assesses the reliability of the assigned values of elements in the data set in relation to their true meaning in the "real world". This uncertainty is usually assessed using contingency tables of agreement between predicted and measured values.

Another parameter of data quality in this case is a resolution that indicates the degree and values of details that are in the area of interest distinguished by space, time and topic. Lower resolution photographs contain a smaller degree of detail and are therefore less accurate. We can also mention time accuracy, which has a major impact on the current validity of the data set and its subsequent use. In LC maps derived by photointerpretation we can also distinguish the quality of interpretation from the positional accuracy of the photograph, which includes several components of data quality. Primarily, it is the attribute accuracy, where the error may be caused by incorrect category inclusion. Much of the uncertainty may also be caused by interpretation subjectivity, which differs by individuals and which leads to different results. Equally problematic is the homogeneity of the resulting layers, because the interpretation is influenced by many factors and because quality in the data set very often varies. The factors influencing this situation include mainly fatigue, stress or the overall mood of the person who carries out the interpretation. The quality of interpretation is therefore highly variable in the data set and, in the case of vector layers, it primarily depends on the human factor. Given that the quality may vary in individual layers, predominantly as a result of interpretation by different persons, it is very important to standardize observation techniques (e.g. a fixed scale for interpretation) and other criteria (e.g. the use of one photointerpretation key) (Lillesand, 2003). As a result, the associated uncertainty of layers obtained affects all subsequent analyses and models. This fact must be taken into account and it must be borne in mind that uncertainty is not only dependent on the quality of the underlying data but also on the end user of this data (Kubíček and Šašinka, 2011). The data set can be evaluated with different degrees of uncertainty, depending on how it will be used. This means that some errors may have a fundamental impact on the intended use, while others will be irrelevant for the given use. Presentation of the degree of uncertainty related to specific parts of the data set can provide the map reader new desired information and help in trust building process as uncertainty awareness influences human trust building on different knowledge generation levels (Sacha et al., 2016).

3. Methodology

To carry out the study, contact copies of aerial photographs of the mining area from years 1966, 1973, 1985, 1994 were used. The aerial photographs were scanned at a resolution of 500 dpi to ensure that even very small details can be distinguished, e.g. residential buildings and surface structure. Individual photographs (time stamps) had a different quality (Fig. 1).

In the aerial images, it was possible to distinguish very small details, such as residential buildings and surface structure. However, there were clear errors in some places, mostly at the edges of aerial images and mainly in older photographs. For this reason, a visualization that highlights such errors was used. The resulting mosaic was created from geometrically corrected photographs, using manual and, in some cases, automated tessellation. Due to the problematic quality of the territory and mostly the photographs from 1966, visual photointerpretation of aerial photographs had to be used. This means that the individual objects in the photographs were assigned qualitative values based on their interpretative features. The visual interpretation of aerial photographs distinguished several basic characteristics: hue, texture, pattern, shape, context and scale (Sabins, 1997). Much of the information could also be obtained from the links between individual elements. The resulting categories of elements were placed into categories derived from the legend of CORINE Land Cover (CLC) (Feranec and Oťahel, 2001), with modified classes and especially with regard to the scale and specific features of the mining area categories. The changes in the legend classification were mainly related to the creation and refinement of mining area categories directly connected with mining. Furthermore, some categories were merged or left only at the second hierarchical level. In the first interpretation, a photointerpretation key was created which further served to identify all objects in the photograph. The quality of aerial photographs did not allow placing some places in the photograph into the relevant category with precision duel to cloudiness and spectral behaviour of the surfaces. For this reason, the parameter of subjectivity was also included in the attribute table. It was the degree to which the surface interpreter was certain about its inclusion in the given category in comparison with other surfaces of the same category. The scale with 5° have been used. With this approach, it was then possible to present the degree of subjectivity of visual photointerpretation and the associated uncertainty. This made it possible to fundamentally distinguish places with low interpretation certainty. From this perspective, it is an essential element, which affects the homogeneity of the entire data set.

The layers were then exported into a geodatabase. To eliminate errors caused by positional inaccuracy, the backward editing method was also used in vectorization. This method eliminates inaccuracies resulting from deviations in aerial photographs or maps. The principle consists in forming the initial layer on the latest time stamp, which is usually transformed into coordinates most accurately. This prevents inaccuracies resulting from shifts of individual objects or land cover types due to different transformation accuracy. Although this method eliminates inaccuracies, there are still inaccurate results and errors. In some places, the shift may not be caused by a transformation error, but a by real change in the position of the surface. Therefore, it is necessary to use this method after careful consideration and also only in places where positional accuracy is known. Emphasis was placed on the issue of demarcation between two categories, which is related to both positional and thematic accuracy. Using visualization techniques, the degree of uncertainty concerning the part of the map in question was demonstrated in terms of inclusion in the correct category, as well as about the possible error due to incorrect definition of the boundaries between individual landscape elements.

4. Visualization methods

The uncertainty visualization of remote sensing data is an important topic covered by several authors (Kinkeldey et al., 2015; McKenzie et al., 2016; Serra and Pons, 2016). Representation of spatial uncertainty has little interest if it does not affect the way people think about their problems to improve their decisions (Deitrick and Edsall, 2008). In order to provide clear and rapid differentiation of places with high uncertainty, several methods were selected. The methods were predominantly external, as these methods are more suitable for displaying detailed areas. First, the *quadtree method* was chosen (Fig. 2a) as a representative of hierarchical data structures that are also useful for visualizing uncertainty (Kardos et al., 2003). This is a very efficient way of displaying uncertainty where the principle is relatively easy to understand. If the difference between the values in one cell is smaller than the set limit, the cell is divided. This process is repeated until the entire area is visualized. The resulting map is still clear, and the attribute importance is also readable. In the final visualization, the areas with small squares show the locations with the highest uncertainty.

The grid method used lines where individual parts were visualized using a grid with different transparency. The transparency of the lines in the grid determines the contained uncertainty (Fig. 2b). The more transparent the grid is, the greater certainty is displayed by the data. The procedure can also be inverted; in such a case the transparent parts show more uncertain areas. This method has to be further tested and always used with caution, due to potential associativity of the method

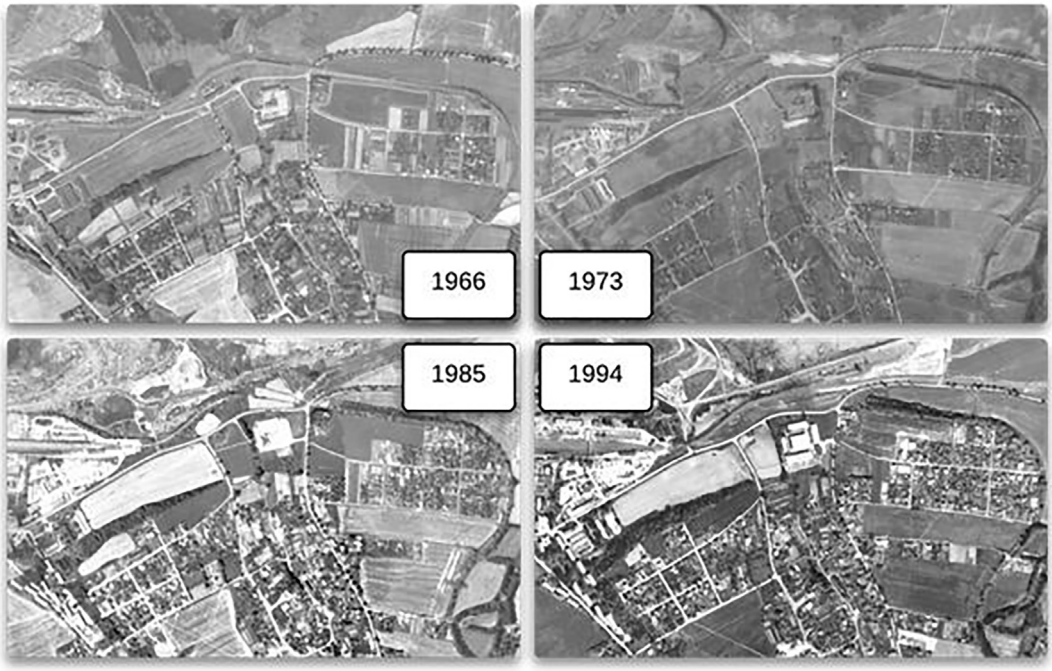


Fig. 1. Different image quality of the Heřmanice mining area in different years.

where transparency very often indicates uncertain data. If certain data was displayed using a completely non-transparent grid, map reading would be very complicated, due to the increasing complexity of the visualization. It is therefore necessary to consider what the primary information is, whether the LC category or the contained uncertainty. The grid method was also applied using modified visual parameters, i.e. different line width with the same applied transparency throughout the map field, where the contained uncertainty is only determined by the line width. In the outcome, this method appears to be relatively easy to understand. The problem is in the line width covering some parts of the map as well as changing colour parameters of the category under the grid. Added geometry, in the form of glyphs (Wittenbrink et al., 1996), was also proposed (Fig. 2c). The method is based on placing the characters whose orientation shows increasing uncertainty. A method using line segments rotating clockwise was chosen. The slightly tilted default value indicating zero uncertainty was chosen deliberately. If the line

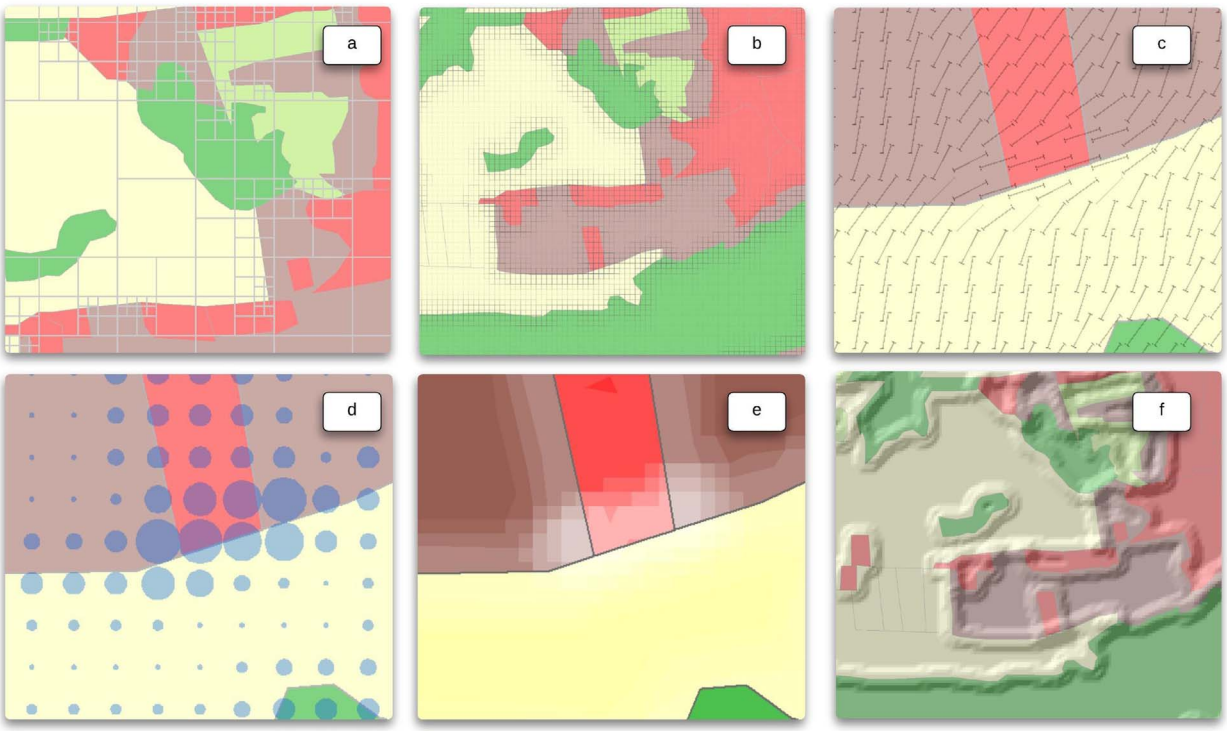


Fig. 2. Visualization of land cover categories in the Heřmanice mining area with contained uncertainty: (a) quadtree method; (b) transparent grid method; (c) glyph method; (d) transparent geometric symbol method; (e) transparency method and hillshade method (f).

segments at zero uncertainty were displayed perpendicular to the x axis, completely different characters would be created as a result of line segment overlap, and legend reading would be complicated. Due to the shape of the line segments, it was only possible to quantify the uncertainty by rotation to the right, by no more than 90°. Larger rotation would again cause character overlap in some parts of the map field. The method, in the form of an arrow rotating around the axis, could also be used to express errors caused by photograph transformation. Another method tested was different sizes of point geometric characters in the form of semi-transparent circles, displayed uncertainty (Fig. 2d). The tint was chosen deliberately, the aim being a colour that was not included at all in the map field. The disadvantages of the method mainly include changes in the colour parameters of the underlying layer due to overlap, as well as optical changes in individual polygon boundaries.

Internal methods as transparency (Fig. 2e) were also used for comparison. Brighter spots indicate uncertain places, with the tint determining the degree of uncertainty. The problem with this method lies in the fact that identical colours are formed in certain places for uncertain phenomena and phenomena that are certain but having different attributes and that are represented by the same tint. The method requires the reader to have a certain degree of imagination and approximation. Moreover, it is only suitable for a limited number of categories and categorical scale. It is not very suitable in established legends, such as in the case of CORINE Land Cover colours. The last methods used in the study were the methods based on the hillshade effect. The difference from the method used to study uncertainty in stable area visualization is that an interpolated 3D model was created to display uncertainty, which was subsequently placed under the semi-transparent layer of individual LC categories (Fig. 2f). Places optically lying above the surface can then be easily distinguished compared to surfaces without contained uncertainty which form a continuous planar surface. The method was also inverted for comparison. In this case, places with higher uncertainty optically lie below the planar terrain, and places without uncertainty are again represented as a planar surface. The advantage of these two methods is the possibility to achieve a smooth course of uncertainty using interpolation. The legend is then only necessary to explain whether there is a positive or negative 3D effect. The disadvantages of this method certainly include the fact that many users reading this map cannot realize that this method is not used for the visualization of a digital elevation model and that it is necessary to connect the third dimension with uncertainty. Yet, for the visualization of uncertainty in LC/LU maps, this method can be useful, because the standard visualization of LC categories is shown in the plane, without the concomitant use of methods for DEM visualization. The method also assumes that the uncertainty will be primarily in the area of the boundaries of individual surfaces, and that a different shape of the imaginary terrain will be provided for the reader which will not be associated with the course of the real terrain. The last complication of this method is the change of colour in the application of layer transparency and combination with the colour of the hillshade layer. From this perspective, the legend must contain the current colour which was created as a result of the overlap of the two layers.

Eye-tracking research using proposed visualizations was conducted at the Department of Geoinformatics at Palacky University, Olomouc on the SMI RED 250 device. Devices sense the positions of both eyes at sampling frequency 120 Hz. The screen resolution used was 1680 × 1050 pixels. Test took place in the laboratory under constant conditions for all tested respondents. The luminous and sound conditions were mostly identical. We tested 14 experts totally. Method of transparent grid and transparent circles were ranked as best within all methods and metrics evaluated. The grid method with a different line width and quadtree method were also evaluated as useful.

5. Conclusion

Proposed visualization brings ways how to visualize uncertainty and cope with the imperfection of visually interpreted LC data and can help to decision making processes. As several other concepts already exist, it is crucial to test proposed methods in accordance to the cognition of individuals. Another problematic point of the whole concept is how to distinguish several uncertainties and combine them in understandable visualization together. For the study, only one join uncertainty value based on combination of positional and thematic accuracy and subjectivity was used. Still, there is no methodology which can cover this problem, and therefore further research within cognitive visualization domain is required. Moreover, research which will take in account real working environment and expertise of people dealing with this kind of data and visualizations is necessary. Nevertheless, still is beneficial to include even some information on uncertainty in the form of visualization as only metadata information is not sufficient due to global values used for the whole dataset. From the point of paper very important element is also a subjectivity of photointerpretation which is normally completely hidden in data.

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APPENDIX 3

Geoparticipation as a tool for mapping calamities mosquito hotspots: A casestudy from Litovelské Pomoraví, Czechia

Rypl, O., Burian, J., Pánek, J., & Brus, J. (2024). Geoparticipation as a tool for mapping calamities mosquito hotspots: A case study from Litovelske Pomoravi, Czechia. *Environmental and Sustainability Indicators*, 24. https://doi.org/10.1016/j.indic.2024.100509

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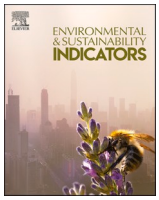
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Geoparticipation as a tool for mapping calamities mosquito hotspots: A case study from Litovelské Pomoraví, Czechia

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ABSTRACT

The coexistence of humans and nature has been a recurring theme throughout history, gaining particular importance in the context of climate change and the sustainability of our planet for future generations. However, the delicate balance between humans and nature is often disrupted, as exemplified by the Litovelské Pomoraví Protected Landscape Area in Czechia, where close interaction between humans and mosquitoes is a persistent issue. In this area, when environmental conditions are favorable for mosquito outbreaks, the local population living near the floodplain forests experiences significant discomfort for extended periods. The risk of mosquito overpopulation has intensified in recent years, largely attributed to climate change. Rising water temperatures in breeding habitats accelerate the developmental cycles of certain mosquito species, shortening the time required for maturation. This study aims to utilize modern geoinformation techniques to assess mosquito activity within the Litovelské Pomoraví region and evaluate the perceived impact on human populations. The methodological approach integrates the development of a representative population distribution layer and participatory mapping. These efforts culminate in the identification of active mosquito zones and the quantification of the at-risk population. While long-term data indicate that the situation is not deteriorating significantly, the study confirms that elevated mosquito activity continues to disrupt the daily lives of residents and visitors. Notably, summer mosquito outbreaks exert a broader impact than spring outbreaks, affecting both a larger geographic area and a greater proportion of the population.

The study's primary output, the spatial delineation of active mosquito zones and the identification of continuously populated areas at risk, holds significant value for the integrated management of the region. These findings can help mitigate the annual occurrence of mosquito outbreaks, improve the health of the floodplain forest ecosystem, and promote biodiversity conservation.

1. Introduction

The magnitude of mosquitoes' role in human life is undisputed — it has been some 100 years since mosquitoes were recognized and incriminated as playing a highly significant part in human affairs (Becker et al., 2010). Mosquitoes (*Culicidae*) are most frequently mentioned in relation to humans because of the diseases they transmit (see e.g. Dworrak and Kiel, 2023; Franklinos et al., 2019; Strelková and Halgoš, 2012), as well as their bites and buzzing (Elbers et al., 2015; Halasa et al., 2014).

Diseases transmitted by arthropod vectors are major contributors to the global burden of infectious disease (World Health Organization, 2017), with nearly half the world's population at threat of infection with a vector-borne pathogen at any moment (World Health Organization, 2014). Mosquitoes represent one of the largest groups of these vectors (Arnoldi et al., 2022; Eritja et al., 2005; Jansen et al., 2021). Their tremendous capacity to transmit infectious and potentially deadly pathogens and parasites makes them the most crucial blood-feeding arthropods worldwide. Malaria (around 212 million cases per year) or dengue (around 96 million cases per year) affect humans and can cause severe diseases or even lethal outcomes (Kilpatrick and Randolph, 2012; World Health Organization, 2017). Chikungunya and Zika virus disease both with 500–700 thousand cases per year are also frequent (Franklinos et al., 2019). In Central Europe, Batai virus, Sindbis virus, Tahyna virus, Usutu virus and West Nile virus could also affect humans (Camp et al., 2021; Holicki et al., 2020; Scheuch et al., 2018). The major driver of

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mosquito vector dispersal is the movement of people and goods. Most of the invasive species were introduced in Europe by international trade of used tires that can be used by mosquito as oviposition site (Giunti et al., 2023). The global use of freight containers to move goods from long distances has, thus, improved the chance of introducing insect species to non-native regions (Becker, 2008; Medlock et al., 2015). The frequency of intercontinental travel and trade and global warming allow foreign species to establish themselves in new environments where their natural enemies are not found (Strelková and Halgoš, 2012). Similarly, anthropogenic changes, such as climate change, urbanization, and environmental pollution, can affect their distribution (Cuthbert et al., 2023; Giunti et al., 2023; Wilke et al., 2021). For example, rising temperatures are creating the conditions for the spread of diseases previously common only in warmer climates. Tropical mosquito-borne diseases have rapidly become a threat to European public health that is proving difficult to confront (Calzolari, 2016; Semenza and Paz, 2021).

Besides these threats to public health, the **biting** and **host-seeking behaviors of mosquitoes** negatively affect humans (Halasa et al., 2014; Hubálek et al., 2010). Large numbers of blood-seeking female mosquitoes can cause a significant nuisance for humans by buzzing sounds or bites that cause itching (Verdonschot and Besse-Lototskaya, 2014). However, the target group includes not only humans but also game animals; for example, a permanently stressed deer may even die of exhaustion (Hubálek et al., 1998; Málková et al., 1974). Mosquito species might be valued as a nuisance when they are present in high densities (Blomgren et al., 2018; Burkett-Cadena et al., 2013), have more than one biting activity per day (Muhammad et al., 2020) and can fly distances over 2 km (Verdonschot and Besse-Lototskaya, 2014). In addition, adult mosquitoes need suitable resting sites and nectar sources in their vicinity, to be able to shelter from adverse weather conditions and predation, and to replenish their energy reserves (Elbers et al., 2015). Tolerance thresholds for the public's perceived nuisance can vary between mosquito species-specific biting and host-seeking behaviors (Dworrak and Kiel, 2023). When mosquitoes disperse into residential areas, mosquito nuisance could affect outdoor activities of the public and lower life quality (Brown et al., 2021; Halasa et al., 2014).

Breeding grounds as well as mosquito dispersal are species-specific (Becker et al., 2020; Verdonschot and Besse-Lototskaya, 2014). Abundance of these sites strongly influence the distance that individual adult female mosquitoes need to fly to lay their eggs (Elbers et al., 2015). The availability and distribution of blood hosts is also an important determinant of the daily **flight range** of mosquitoes (Bailey et al., 1965; Elbers et al., 2015). Some mosquitoes are poor fliers, while others can fly longer distances (Becker et al., 2010). These typical niches can be linked with landscape type – weak fliers are often found in urban domestic and in-forest environments, weak to moderate flyers occur in woodlands, and strong fliers can be found in more open areas (Verdonschot and Besse-Lototskaya, 2014). As stated in Elbers et al. (2015), the dispersal of adult mosquitoes can be generally classified into long-range and short-range dispersal (see Service, 1980, 1997). Long-range dispersal is often unintentional, aided by wind (i.e. strong winds that carry swarms of mosquitoes downwind) or human transport (transporting goods and passenger flights), and the distances between origin and destination can be up to hundreds of kilometers apart. On the other hand, short-range dispersal is often intentional. A further distinction can be made between non-oriented and oriented flight towards host location and attraction (Service, 1997) and are mediated by host-derived cues, such as odors (lactic acid, ammonia, fatty acids, CO_2), as well as humidity and body heat (Sutcliffe, 2010; Takken, 1996). This dispersal eventually results in a blood meal (Elbers et al., 2015). Non-oriented flights aim to increase the likelihood of encountering a host – species-dependent but also strongly influenced by the environment and thus sensitive to environmental change. Temperature, humidity, illumination, wind and local topography are key environmental determinants of non-oriented short-range dispersal. For example, drastic reductions in mosquito catches have been observed when the temperature dropped below 16 °C (Bidlingmayer, 1964). Moonlit nights have a positive effect on mosquito activity, probably because the light intensity of the full moon is close to the level at twilight (Bidlingmayer, 1964; Kampango et al., 2011). Intrinsic drivers of non-oriented flight include the mosquito's physiological status, such as egg maturation, mating status and energy balance (Klassen and Hocking, 1964). As for mosquito flight distances, average distances are comparable among mosquito genera, with recorded average maximum distances of 3 km for *Aedes*, 3.5 km for *Anopheles*, 5 km for *Culex* and 7.6 km for *Ochlerotatus* (Verdonschot and Besse-Lototskaya, 2014). Nevertheless, there are large variations within these genera. Some species, such as *Aedes polynesiensis*, *Aedes scutellaris*, and *Ochlerotatus rusticus*, have a very limited dispersal capacity of 50–100 m. In contrast, others are known for their strong dispersal abilities, including *Ochlerotatus taeniorhynchus* (32 km), *Anopheles freeborni* (35 km), *Aedes cantator* (48 km), and *Aedes sollicitans* (48 km; see in detail Verdonschot and Besse-Lototskaya, 2014).

Climate (and weather) affects not only the transmission of infectious diseases but also **mosquitoes' biological processes**. Dipteran vectors such as mosquitoes usually have a short life cycle, with full development from egg to hatch through four larval instars, pupation and then emergence as adults taking one week to months and development of each stage within days (de Souza and Weaver, 2024). Each female mosquito can lay 100 to 250 eggs in each clutch. Mosquito eggs can be broadly categorized into rapid-hatch eggs and delayed-hatch eggs (Hawkes and Hopkins, 2021). Rapid-hatch eggs are deposited directly on or near the water's surface and hatch within a few days. In contrast, delayed-hatch eggs are usually laid near water or on moist soil or vegetation some distance away. These eggs can endure for extended periods (months or even years) due to their resistance to drying out and ability to withstand extreme temperatures, including freezing winters. Dale and Knight (2008) specify that the timeframe for a complete cycle may be as short as five days in tropical and subtropical environments, and there are differences between species in terms of their development times. Climate change and the associated temperature rise may result in a significant shortening of the development cycle. This is confirmed by de Souza and Weaver (2024) when they mention temperature, humidity and precipitation affect fecundity, reproduction and inter-stadial developmental rates of the vector. Vector activity, biting rate and transmission probability all respond to temperature variations, whereas temperature also has an impact on the development between stages, according to them. All mosquitoes have an intimate relationship with wetlands, and water is an essential requirement for the larval stages (Dale and Knight, 2008). Changes in the hydrological regime and water and air temperatures are the key factors influencing mosquito species' composition, abundance, and ecology (Strelková and Halgoš, 2012). Intense precipitation may create more suitable aquatic environments for oviposition, larval development and survival of some vectors owing to the formation of stagnant water pools, the high humidity and surface moisture (de Souza and Weaver, 2024).

Recently, spring and summer in central Europe have been characterized by significant air temperature fluctuations. Precipitation has been irregularly spread during the year, in contrast with normal conditions featuring long dry periods alternating with heavy rains, which caused localized or extensive floods with mosquito calamities (Olejníček et al., 2003). **Changes in climatic conditions** lead to changes in the phenology of mosquitoes. Some mosquito species have reproductive cycles strongly associated with flooding (often called floodwater mosquitoes), such as *Aedes vexans* and *Aedes ochraceus* (de Souza and Weaver, 2024). Schäfer and Lundström (2014) also mentions *Aedes stictichus* species. Floodwater mosquitoes lay their eggs, which can remain viable for many years, individually on moist soil above the water line to await flooding, leading to explosive populations following heavy rainfall or tidal flooding (Diniz et al., 2017). Strong winds associated with flooding storms may kill many adult mosquitoes if safe resting locations are not abundant (de Souza and Weaver, 2024). Floodwater mosquitoes then pose an immense nuisance to the local population

living near these wetlands (Becker, 2006; M. L. Schäfer and Lundström, 2014). In Czechia, mosquito calamities frequent in the floodplains of the Morava River with various types of stagnant waters, which offer suitable conditions for mosquito breeding – and are documented mainly through studies related to the lower course of the river, in South Moravia region (see e.g. Berec et al., 2014; Minář et al., 2001; Olejníček et al., 2003; Palička, 1967; Šebesta et al., 2012). The water regime of the floodplain forests of Moravia is very favorable for the regular and often mass occurrence of various mosquito species. The best conditions for larval development are provided by the floodplain forests for mosquitoes of the genera *Aedes* and *Ochlerotatus* (Strelková and Halgoš, 2012), which are decisive contributors to **mosquito calamities**. Calamity states are defined by the number of stings per minute in populated areas. For instance, in the Czechia, a calamitous occurrence is a situation where ten or more attacks per minute are recorded in the built-up area of a municipality outside the time of peak activity (Šebesta et al., 2012). Hygienists consider this value to be the limit of an acceptable load, and exceeding it poses a significant threat of harm to human health. Spring calamities are most often caused by early or late spring species that are univoltine (monovoltine), i.e. they produce only one generation per year. These include *Ochlerotatus cantants*, *Oc. communis* and *Oc. cataphylla* (Alekseev et al., 2007). Earlier snow melt and spring precipitation could result in a shift in the larval development of the spring univoltine species (Minář et al., 2007). Summer calamities are caused by summer species, which are multivoltine – they can produce more than one generation per year, but most often two or three. These are the late spring and summer species *Ochlerotatus sticticticus*, *Aedes vexans* and *Aedes cinereus* (Alekseev et al., 2007). The designation of spring or summer mosquito species should be understood as the period of their most frequent breeding, not as the period of actual adult emergence, which may be longer. The length of the developmental phase of mosquitoes varies considerably between spring and summer species. The period of inundation of the area, which allows their development, and the water temperature play a key role. Temperature determines the rate of larval development. Eggs can hatch shortly after flooding if the water temperature exceeds 9 °C. Temperature determines the rate of larval development, a process that can be as rapid as 1 week at 30 °C and up to 3 weeks at 15 °C (Vaux et al., 2021). Larval development can be rapid in temporary water bodies that remain wet from just a few days to several weeks, such as flooded meadows and low-lying areas with willow and reed (Becker et al., 2010). Eggs can survive up to 5 years if no flooding occurs after oviposition, with eggs normally spending the colder months – September to March – in diapause (Vaux et al., 2021). When flooding, eggs hatch in response to oxygen depletion, and not all hatch synchronously. The species adopt instalment hatching to maximise the survival of the populations should aquatic habitats dry out before adult emergence. Where conditions support development, huge larvae can be found with hundreds per litre and more than 100 million per hectare (Becker et al., 2010), the subsequent emergence of adult mosquitoes reaching biblical proportions. This mass emergence creates pressure for seeking blood meals, and females may be forced to migrate up to 15 km from their breeding grounds, with these founder sites leading to significant migration to other potential habitats (Petrić et al., 1999) and deter all normal human activities.

Reducing the threat of mosquito problems is then most effectively done at the larval stages when the larvae are spatially concentrated (Dale and Knight, 2008). It should be noted that the larvae are not a problem for humans, but it is important to prevent the adults from hatching and spreading into the surrounding area. Therefore, control by larvicides is based on source reduction of possible adults. Recently, efforts to drastically eradicate mosquitoes, that could lead to irreversible damage to the environment (nature), have been retreating. Some shifts are already evident in the study by Dale and Hulsman (1990), which, in the salt marsh context, have adopted a more benign approach, seeking to alter the environment minimally. They believe that relatively subtle changes can affect mosquitoes without destroying wetland function. In support of this, Mokany (2007) and Schäfer (2004) mentioned that mosquitoes abundant in ephemeral wetlands can significantly affect ecosystem processes and functions and, thus, the wetland value. Moreover, once emerged as adults, mosquitoes transfer huge volumes of biomass into the terrestrial food web, in turn contributing to the diets of insectivorous mammals, birds and other invertebrates (Hawkes and Hopkins, 2021). Mosquitoes belong to the group of bioindicators (Chowdhury et al., 2023), i.e. organisms used to monitor certain characteristics that help assess the degree of environmental changes occurring in an ecosystem (Alencar et al., 2021; Jardine et al., 2008). Bioindicators of such changes may include shifts in density or the disappearance of certain species (Chaves et al., 2016).

Mosquitoes, in relation to the ecosystem, perform a useful function and increase the value of the environment. Conversely, mosquitoes in high concentrations reduce the quality of life of the population living in close contact with nature. The solution is integrated territory management, considering both the environmental and social aspects – which should be evenly balanced. However, to intervene responsibly, it is first necessary to map the current situation in the area. Surveillance is essential to any integrated mosquito management program designed for native and non-native mosquitoes in natural, protected areas or urban settings (Martinou et al., 2020; Osório et al., 2014). Understanding mosquitoes' distribution, abundance and seasonality at the local scale is necessary for any risk assessment to be possible (Schaffner et al., 2013). Knowledge of the presence and current range of mosquito species occurrence in a given area is crucial to assessing the potential threat to human and animal health (Jawień et al., 2024; Strelková and Halgoš, 2012). Typically, mosquito surveillance is conducted by trained professionals, including medical entomology experts, public health officials, and researchers. This process demands substantial expertise and resources, encompassing personnel, equipment, and time (Martinou et al., 2020). The public can also contribute towards recording mosquitoes through citizen or community science projects where non-experts get involved in scientific research (Pataki et al., 2021). **Citizen science** can enhance and facilitate mosquito surveillance undertaken by authorities at the local level, ensuring better geographic coverage at a finer scale and providing essential information on mosquito diversity, distribution and habitat preferences (Braz Sousa et al., 2020; Palmer et al., 2017; Pernat et al., 2021). Citizen scientists, guided by experts and provided with mosquito identification keys, can contribute to mosquito recording by either collecting and submitting mosquito specimens to the experts or using mobile application technologies (Martinou et al., 2021). The active involvement of citizen scientists can enable data collection and overcome accessibility or transboundary limitations due to political or financial reasons (Pernat et al., 2021). Citizen science projects can contribute towards early warning rapid response systems by informing the authorities and the public. For this purpose, it is advisable to use geoparticipation tools, which involve local people who know the conditions and situation in the area in mapping mosquito activity.

Citizen engagement in decision-making through geoparticipatory spatial tools is one of the new research streams in socio-economic geography, behavioral geography, geoinformatics, political science and many other fields. In the last decade, participatory mapping methods or geoparticipatory tools have gained popularity among citizens and local government representatives who interact with citizens through digital technologies (Kahila-Tani et al., 2019; Mukherjee, 2015).

The concept of **geoparticipation** can be understood as usage of spatial tools to engage citizens in decision-making processes that affect them (Pánek, 2016). Most often, this involves making decisions about a public space, but it can also involve sharing information or perceptions about the environment in which they live. Although there is not yet a universally accepted definition, it can be understood as an umbrella term for technologies and approaches that enable citizens to engage in decision-making through map-based applications – whether analogue or digital. This decision-making often takes place regarding activities

located in public space. Geoparticipation refers to using methodologies and tools that facilitate citizen engagement in decision-making processes related to spatial planning and resource management. This approach prioritizes the empowerment of communities by incorporating their local knowledge into formalized planning frameworks, thereby enhancing the inclusivity and effectiveness of governance practices. However, with the development of information technology, web-based and often mobile applications oriented towards collecting subjective and objective spatial information are increasingly coming to the fore (Falco and Kleinhans, 2018). It is worth mentioning, for example Bästa Platsen (Sweden), Carticipe-Debatomap (France), Commonplace (United Kingdom), CoUrbanize (USA), Social Pinpoint (Australia), Pocitové mapy (Czechia; in English as Emotional maps). These applications can be used for one-off data collection (e.g. creating a transport strategy or revitalising a housing estate) and for longer-term communication and information exchange between city/municipal authorities or researchers on the one hand and citizens on the other. Geoparticipation often employs participatory GIS (PGIS) techniques, which combine traditional GIS with participatory approaches. This includes using analogue (sketch maps) and digital (online platforms) environments. The primary benefits of geoparticipation include enhanced civic engagement, as it promotes broader citizen involvement in local governance processes. It also leads to improved decision-making by incorporating diverse perspectives, resulting in more informed and comprehensive policy development. Furthermore, geoparticipation fosters community empowerment by providing local groups (with local spatial knowledge) with tools to express their concerns and actively influence decision-making outcomes.

2. Objectives

A particular example of geoparticipation using modern geoinformation methods is the participatory mapping and assessment of mosquito activity conducted in 2023. This initiative is part of the methodology of integrated management of the area to minimize annually recurring calamitous mosquito populations with regard to improving the condition of the floodplain forest ecosystem while maintaining and strengthening biodiversity in the Litovelské Pomoraví Protected Landscape Area (from now on referred to as "Litovelské Pomoraví PLA" or just "PLA").

This protected landscape area is located in north-central Moravia. It is situated along the Morava River. The local abundant water and wetland ecosystems are ideal breeding grounds for mosquitoes. The characteristics of this area are very close to those of the areas on the lower Morava River described in the studies mentioned in the Introduction chapter. When nature provides suitable conditions for developing their larvae, mosquito calamities afflict residents living in contact with the floodplain landscape for many weeks. As explained above, the threat of mosquito overpopulation has been exacerbated in recent years by climate change (Dale and Knight, 2008) – as water temperatures in the mosquito breeding grounds could rise quickly, the time required for the development cycle of mosquito species is shortened. At the same time, unpredictable weather patterns and flash floods occur more often.

Besides presenting a new, innovative, and universally applicable method of mapping mosquito calamity hotspots, the authors also provide a view of the current situation in the middle course of the Morava River. Related studies – either in terms of spatial delineation or simple assessment of activity during mosquito calamities – have not adequately addressed this area. The study on mapping of calamitous mosquito hotspots, which is the subject of this paper, is based on the following objectives:

A) to investigate the impact of this activity on humans;
B) to assess mosquito activity in a specific research area in the long term;
C) to spatially delineate the active zones;
D) to identify the affected population and define its spatial extent.

In the context of these objectives, the following two additional hypotheses were formulated:

I. Mosquito activity is worsening in a specific research area.
II. Summer mosquito calamities are more severe than spring calamities and have a greater impact on the humans.

The following three groups of respondents represent the target group of the study:

- residents permanently living in the specific research area;
- owners or users of secondary housing in the specific research area (cottage, cottage);
- visitors-tourists who visit the specific research area on a short-term and infrequent basis.

3. Data and processing procedure

For the study on mapping calamitous mosquito hotspots, a specific research area (see map in Fig. 1) was defined, which consists of the territory of all 22 municipalities through which the Litovelské Pomoraví PLA traverses. The specific research area covers an area of 465 sq. km (including 93.30 sq. km of the PLA).

The fulfilment of the defined research objectives A–D was carried out through the following three segments:

- Design and creation of representative population distribution data layers,
- Design and development of the questionnaire survey,
- Identification of active zones and quantification of the affected human population.

In a comprehensive form, it can be described as the first two segments of data acquisition and processing that enter into an overarching framework that deals with their integration and evaluation.

3.1. Representative population distribution data layers

The initial prerequisite for implementing the above research objectives is to have information on the distribution of the population in the specific research area. Traditional data sources (such as national registers) and their products capturing population distribution in space provide only a static view linked to the population's residence or workplace, which is inaccurate and can be highly misleading. An example of a weakness is the common consideration of a person's permanent residence, which may not sufficiently reflect the actual situation – in practice, it is common for a person to live in a different place than the one where they are registered for permanent residence. At the same time, a faithful description of the population distribution cannot be based on just one data source. It follows that the product of one layer (capturing only partial population state) is insufficient to describe the distribution; it must be the product of several variants.

This paper followed the methodology of Rypl and Burian (2023), which describes in detail the aggregation of several data sources (Czech national registers) to create a population grid in two basic variants – daily and night. So, it assumes that the distribution of the population varies between day and night, as well as on weekdays and weekends. The nature of the study does not allow data aggregation into administrative units (cadastral areas of municipalities or parts thereof), as is often the case. On the contrary, this would significantly reduce the data's positional accuracy, making any investigation of spatial differentiation more difficult. Therefore, a grid (a regular grid through which a specific study area is divided into cells of the same shape and size) was used to allow the absolute population values to be relativized to the area

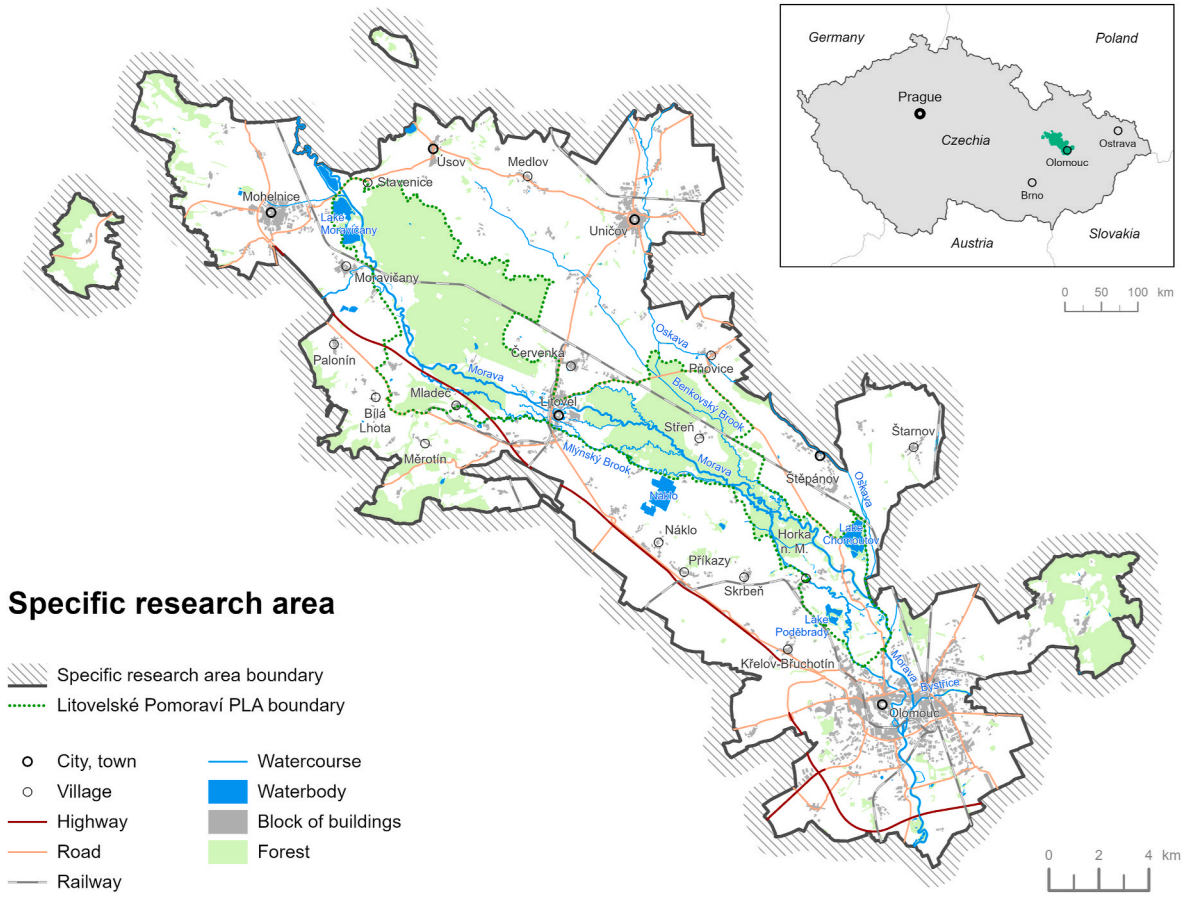


Fig. 1. Location and definition of the specific research area.

and maintain the necessary level of positional accuracy The procedure is described as a set of methodological steps linked to technical implementation in a GIS environment (ArcGIS Pro software). In the relevant part of the processing procedure, individual geospatial operations are indicated in brackets and italics.

Table 1
Overview of input data used for creating population distribution data layers – adapted from Rypl and Burian (2023).

	Input dataset (Data layer)	Level of detail	Year	Provider (*Source*)
1	Population	Address point	2021	Czech Statistical Office (*Population Census*)
2	Number of economically inactive and unemployed		2021	Czech Statistical Office (*Population Census*, *Register of Enumeration Districts and Buildings*)
3	Number of workers, employees		2022	Czech Statistical Office (*Register of Economic Entities*)
4	Number of children, students Number of teachers and school staff		2022	Regional Authority of the Olomouc Region, Czech Statistical Office (*Register of Enumeration Districts and Buildings*)
5	Number of seniors/retirees		2022	Ministry of Labor and Social Affairs of the Czech Republic (*Register of Social Service Provider*)
6	Specific research area	Group of municipalities (own delimitation)	2022	State Administration of Land Surveying and Cadaster (*Registry of Territorial Identification, Addresses and Real Estates*)

As can be seen from Table 1, six supporting datasets were used for aggregation when creating the population grid. Most are carrier datasets with information about the population (1–5) and one set representing the specific research area (6). These are mainly data from the Czech Statistical Office (Population Census, Register of Economic Entities), data from the registers of the Regional Authority of the Olomouc Region and the Ministry of Labor and Social Affairs of the Czech Republic (Register of Social Service Providers).

The night population state, which assumes the presence of the population in their homes, is based on the simple number of usual residents (Data layer 1; see Table 1). After creating a regular grid with a spatial resolution of 100 m × 100 m (*Create Fishnet* tool in ArcGIS Pro), the point records of the Population layer were aggregated at the level of each grid cell (*Summarize Within*). Subsequently, the vector output of the aggregated data was converted to a raster (*Feature to Raster*).

On the other hand, the daily state is more complex – it combines the numbers of economically inactive and unemployed, the numbers of workers and employees, the numbers of children, pupils and students, teachers and school staff, and the number of seniors (Data layers 2–5). As in the previous case, the initial step was to generate a regular grid with a spatial resolution of 100 m × 100 m for the specific research area (*Create Fishnet*; Data layer 6). Then, sub-aggregations of Data layers 2–5 were performed, summing the corresponding point records for each layer at the grid cell level *(Summarize Within*). These aggregates were then combined (*Union*) and summed again (*Calculate Field* with activated *sum* function) to produce the final aggregated layer in vector form, which was converted to a raster (*Feature to Raster* tool in ArcGIS Pro). These daily and night population states are relative to the working day. Capturing the population's behavior at the weekend, including the prediction of their concentration, is difficult to implement, as it depends

on individual behavior and the specificities of the territory concerned, which are difficult to measure.

The aggregation procedure is explained in detail in the methodology of Rypl and Burian (2023) on pages 38–41. The output data layers describing the population distribution in the specific research area are visualized in Fig. 2 with variant differentiation of daily and night population states.

After presenting a global view of the population distribution in the specific research area, it is convenient to proceed to a specific population quantification and approximate the differences between day and night at the level of specific municipalities. The summary table (see Table 2) shows for all municipalities in the specific research area the maximum (i.e., maximum pixel value), average (μ), and total (Σ) values of the daytime and nighttime population in the workday condition. Moreover, the total value of the respective state can be compared with the official population value of 2022.

For larger settlements (over 2,000 inhabitants), the table shows a significant difference between the total daily population value and the official estimate for 2022. This is mainly due to the vagueness and ambiguity of data from the Register of Economic Entities in Czechia (Dataset 3 in Table 1). The Discussion section identifies and explains this and other reasons.

The deviations of the projected daily and night population (S_P) from the official population estimate for 2022 (S_e) are shown in Table 3, where a positive (+) deviation indicates an overestimate and a negative (−) underestimate. While the raster reflecting the night population reaches adequate accuracy, in the case of the daily population, the deviation increases significantly with increasing settlement size – the largest overestimation occurs for the most populous settlements, while smaller settlements of up to 1,000 inhabitants are estimated quite faithfully. Given the settlement structure of the specific research area (i.e. the dominance of smaller settlements), the deviations were considered adequate for the research design. However, to remove the adverse effect of larger settlements, average deviations will be subtracted at the level of individual municipalities to achieve the highest possible accuracy. It should be noted that the usual residence is compared with the official population estimate based on permanent residence – deviations at a reasonable level are, therefore, perfectly natural.

3.2. Creation of the questionnaire survey

Adequate data were necessary to assess and evaluate mosquito activity in the Litovelské Pomoraví and the impacts of this activity on humans. Due to the phenomenon's nature, a questionnaire survey was decided upon, as mosquito activity is related to humans and cannot be measured by instruments directly in the field and expressed in conventional quantities. Combined with the population distribution data, it is then possible to quantify the population in areas with increased mosquito activity and take measures leading to an increase in the quality of life in this specific research area.

The essential requirements for the technical platform are the ability to draw on the map (point and area features) and to relate data to this relevant location in space (detailed map required). It is also necessary to ensure the conditional behavior of the questionnaire. Simply asking questions, selecting from predefined answers, and writing the answer in a text field are now standard in most form-building platforms. In line with the previously formulated requirements and the questionnaire structure outlined above, the Pocitové mapy platform (Emotional maps) was chosen for the subject survey – concrete example in Fig. 3. ArcGIS Survey123 and ODK Collect could also be used.

The questionnaire was intuitive and user-friendly. The respondent first marked on the map in the form of a point or area the places where he/she is aware of increased mosquito activity, and for each defined place respondent specified the level of activity on a scale of low, rather low, rather high, high or not assessable via a pop-up window – both for the spring and summer months and in aggregate for the year 2023. The respondent then proceeded to fill in the general form, providing personal data in addition to the socio-demographic classification of the respondent (age, gender, place of residence). The questionnaire consisted of the following questions (*the prescribed answer options are given in brackets*).

- Concerning the specific research area, which population group do you belong to? (*permanent resident*; *secondary housing owner or user*; *visitor-tourist*),
- Indicate the level to which mosquito activity limits you during your stay in the specific research area. (*does not limit*; *rather does not limit*; *rather limits*; *limits*),

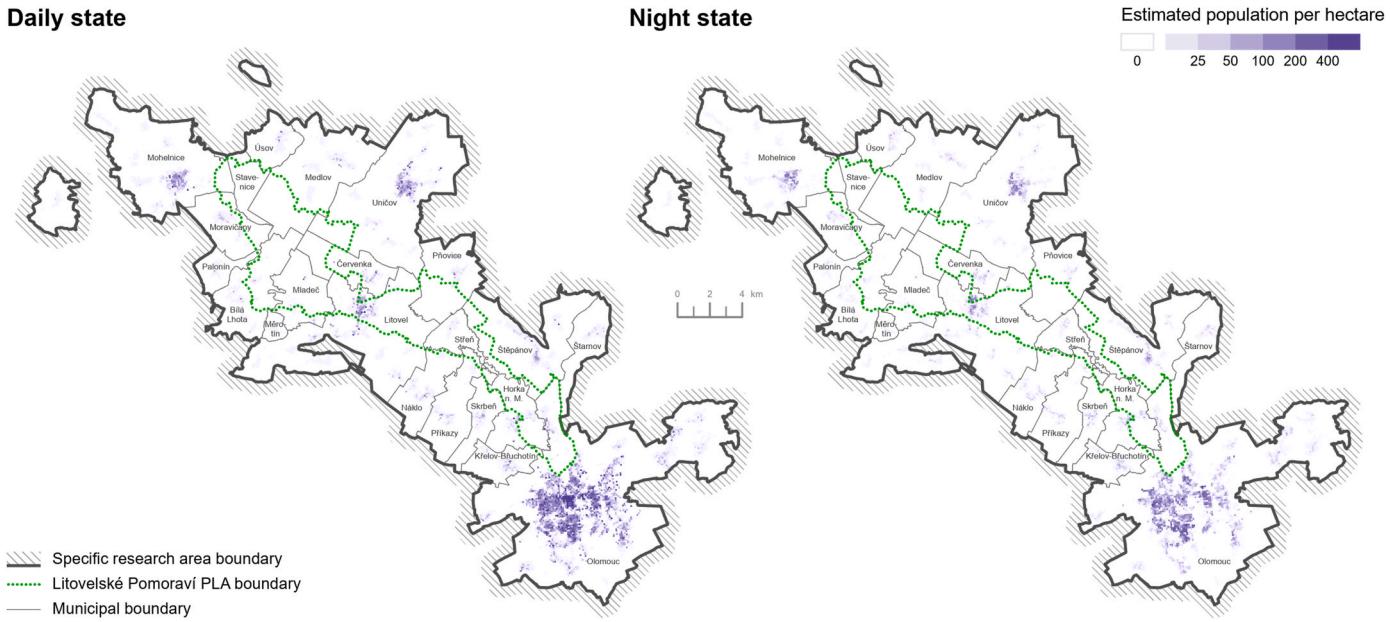


Fig. 2. Population distribution in the specific research area.

Table 2
Summary of daily and night population distribution in the municipalities of the specific research area

Municipality	Population (2022)	Daily state of population			Night state of population		
		max.	μ	Σ	max.	μ	Σ
Olomouc	99,496	7,503	25.72	265,860	1,563	10.20	105,419
Uničov	11,066	2,259	3.88	18,520	266	2.27	10,963
Litovel	9,567	768	3.39	15,758	297	2.04	9,477
Mohelnice	9,103	3,503	3.61	16,701	309	1.98	9,143
Štěpánov	3,512	1,076	2.09	5,583	112	1.26	3,385
Horka nad Moravou	2,577	656	3.23	3,866	90	2.07	2,475
Křelov-Břuchotín	1,749	378	3.11	2,464	68	2.21	1,752
Medlov	1,626	175	0.61	1,902	53	0.50	1,570
Náklo	1,504	326	1.60	1,831	50	1.26	1,445
Červenka	1,445	264	1.82	2,060	115	1.31	1,490
Moravičany	1,324	92	1.25	1,515	48	1.02	1,240
Příkazy	1,316	186	1.13	1,584	46	0.90	1,263
Skrbeň	1,160	137	1.74	1,363	72	1.42	1,115
Bílá Lhota	1,152	186	0.70	1,283	36	0.61	1,106
Úsov	1,139	241	1.34	1,252	57	1.17	1,087
Pňovice	1,010	208	0.80	1,317	50	0.60	988
Štarnov	846	68	0.89	884	46	0.83	819
Mladeč	716	221	0.86	1,033	93	0.63	754
Střeň	600	76	0,83	487	40	0,99	582
Palonín	351	73	0,62	331	32	0,62	331
Měrotín	263	28	1,16	251	25	1,17	252
Stavenice	135	27	0,24	157	22	0,20	127

Table 3
Deviation of the projected population from the official 2022 population count

Settlement category by population	Mean deviation $S_P - S_e$	
	Daily state	Night state
< 1 000	+100.57	−1.55
⟨1 000; 2 000)	+515.10	−31.03
⟨2 000; 5 000)	+1,336.16	−88.87
⟨5 000; 10 000)	+4,879.00	−104.00
⟨10 000; 15 000)	+8,987.25	−43.00
> 15 000	+5,8258.2	+1,259.4

- How do you try to reduce/limit/eliminate mosquito activity? (*use of repellents*; *contact killing at the site of occurrence*; *cancellation of visit/stay or rescheduling*; *otherwise*),
- How do you assess mosquito activity in a specific research area in the long term? (*worsens*; *rather worsens*; *no change*; *rather improves*; *improves*; *cannot assess*),
- Are you getting enough information about mosquito calamities in Litovelské Pomoraví? (*yes, to an adequate extent*; *yes, but i would like more information*; *no*).

If the respondent has signed up for the visitor/tourist group, he/she

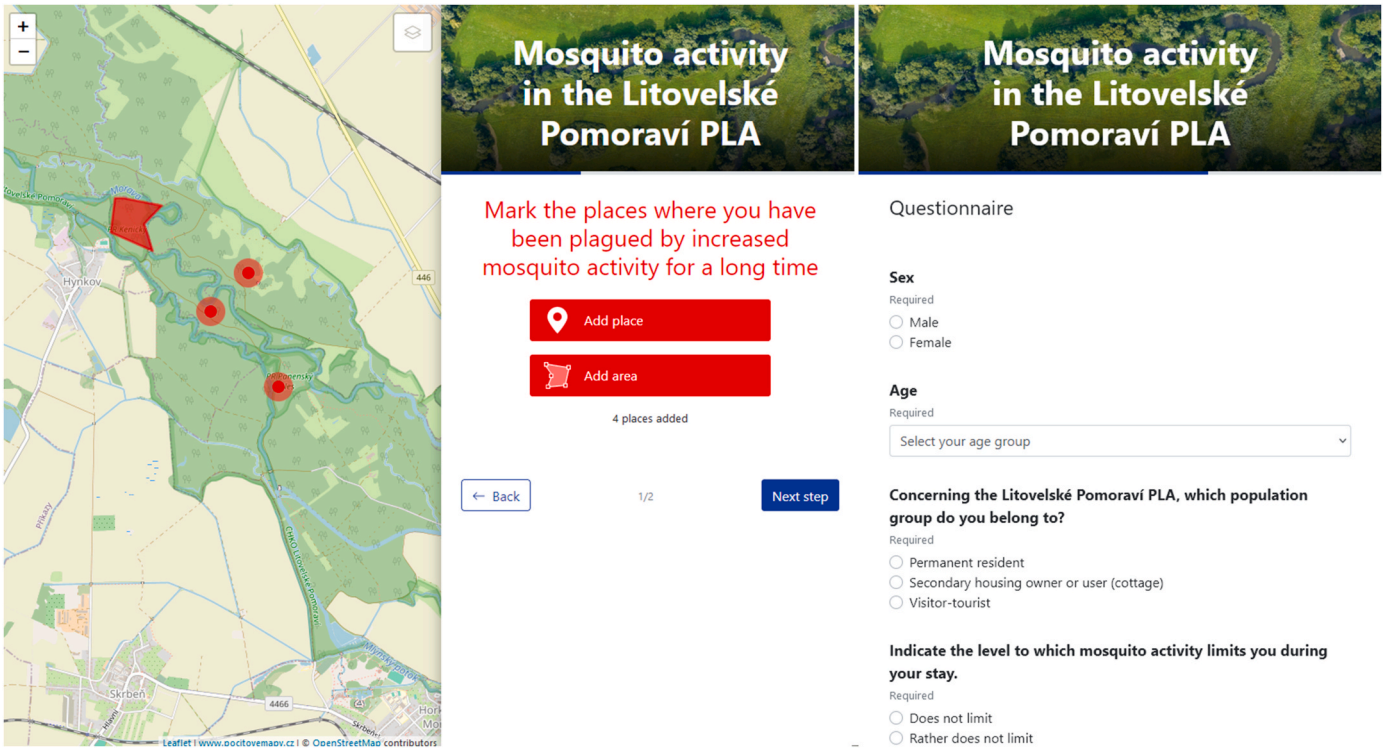


Fig. 3. Sample online questionnaire with map (originally in Czech; translated).

has also answered the following questions.

- How often do you visit a specific research area in the summer? (*less than 3 times* per *month*; *3 to 6 times* per *month*; *7 to 10 times* per *month*; *11 to 14 times* per *month*; *15 or more times* per *month*)
- What is the usual purpose of your visit? (*hiking*; *water recreation/ swimming*; *cycling or inline*; *other purpose of visit*)

3.3. Questionnaire evaluation, identification of active zones and quantification of the affected population

In the initial phase, data export and filtering of records of respondents residing outside the specific research area was carried out – these were mainly 43 respondents permanently living in Hlušovice, a village located outside the specific research area (respondents from Hlušovice reported as visitors-tourists were, however, in the respondent's sample).

Subsequently, a general evaluation of the results of the respondents' form data was carried out, consisted of constructing graphs and charts in a spreadsheet environment, using pivot tables.

However, the main focus was on the extensive phase of delineating active zones. The key input attributes were mosquito activity data in the spring and summer months, mosquito activity data in 2023, and the corresponding geometries (points, polygons) related to these data. First, a numerical rating was made for each (partial) mosquito activity degree according to Table 4, where the individual word labels for the states were numerically scaled by values from the interval $\langle 1;5\rangle$, thus creating the new variables I_{spring}, I_{summer} and I_{2023}.

The values of these partial mosquito activity degrees were also averaged to produce a single aggregate value $I_{\bar{x}}$ reflecting seasonal variability, for which $I_{\bar{x}} = \frac{I_{spring} + I_{summer} + I_{2023}}{3}$, where $I \in \langle 1;5\rangle$. The transformation of the word states to numbers, together with the calculation of the aggregate value, was successively applied separately to both polygon and point records.

Then, records with polygon geometry – separately for each of the variables I_{spring}, I_{summer}, I_{2023} and $I_{\bar{x}}$ – were unioned and aggregated by area. The arithmetic mean was calculated for the overlapping (identical) areas, which resulted in a compromise valuation of the sub-areas across respondents (hereafter referred to as the **a-value**). The issue of overlapping geometries did not need to be addressed for the point records, so the original values of I_{spring}, I_{summer}, $I_{\bar{x}}$; were further assumed **(b-value)**.

In the next phase, a regular square grid with a spatial resolution of 100 m × 100 m was generated with the reference parameters used to create of the population grid. The spatial join was then used to assign a-values (polygons) to individual grid cells, and a similar process was followed for points (b-values). Geometric union followed by c-value creation produced the resulting mosquito activity degree value with resolution to individual grid cells **(c-value)**. The formation of the c-value was carried out according to the following criteria.

- If the a-value and b-value are defined, then calculate the c-value as the arithmetic mean of the a-value and b-value;
- If a-value is defined and b-value is not defined, then c-value is equal to a-value;
- If b-value is defined and a-value is not defined, then c-value is equal to b-value;
- If neither a-value nor b-value are defined, then c-value is also not defined;

Whereby this part of the procedure was performed repeatedly for I_{spring}, I_{summer} and $I_{\bar{x}}$. Since a-values and b-values are defined on the interval, a zero value cannot occur. The resulting mosquito activity rasters then use the following scaling intervals (see Table 5).

The diagram in Fig. 4 simplifies the process of formation of the active zone layer.

In addition to the baseline layer of active zones, a variant was created that reflects the location of mosquito breeding grounds identified within the prediction and management of calamitous mosquito populations project (more information in the Funding section) into the originally defined active zones resulting from the questionnaire survey. The envelope zones created through buffering at distances of 100, 500 and 1000 m from the geometric center of the breeding grounds, after conversion to a raster and reclassification, were coded with the numbers 3 (for 100 m), 2 (for 500 m) and 1 (for 1000 m) according to their predicted threat. For example, the nearest pools are weighted at 3, and the furthest pools are only assigned a weight of 1. The grid resolution of the envelope zones is consistent with that of the population grid, i.e., the size of a single cell corresponds to 100 m × 100 m. The total active zone score was then simply given by multiplying the original active zones $\langle 1;5\rangle$ with the raster of the envelope zones of the pools in the interval $\langle 1;3\rangle$. The resulting continuous variable of the total score, defined by the interval $\langle 1;15\rangle$, was divided by the natural breaks into five groups in the visualization, characterized by minimal within-group differentiation and, conversely, by the greatest possible differences between the groups themselves. This configuration ensured the differentiation of high-activity to low-activity areas, crucial for interpreting the resulting data and further inference.

The final quantification of the affected population was then performed using the zonal statistics, where the input raster of values was the population raster (in the daily and night state variant), and the newly created active zone raster **(**c-value – respectively total score – in the spring and summer, and overall trend variants) was used as the zone raster.

The creation of population threat degrees for daily and night population states was based on the min-max normalization of population state values and mosquito activity degree (total score) by the formula $y_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)}$, where y_{ij} is the new transformed value of the variable, x_{ij} corresponds to the i value of the variable j and x_j corresponds to the set of all values of the variable j – in combination with the function *min*, *max* means the minimum or maximum value of the set of all values of the variable x_j; then multiplying them. Visualization of the mosquito-threat population can be used to visually identify a group of breeding grounds where eradication measures are to be carried out as a priority, with the goal of improving the quality of life of people in mosquito-threatened populated areas.

4. Results

One hundred five respondents participated in the survey, 48 of

Table 4
Numerical rating of the states forming the partial mosquito activity degree

Partial mosquito activity degree (consolidated for spring, summer, year 2023)	Score
Cannot be determined or not filled in	1
Low	2
Rather low	3
Rather high	4
High	5

Table 5
Scaling intervals of resulting mosquito activity degree

Mosquito activity degree	Interval (c-value)
Not clearly identifiable	$\langle 0;1\rangle$
Low	$\langle 1;2\rangle$
Rather low	$\langle 2;3\rangle$
Rather high	$\langle 3;4\rangle$
High	$\langle 4;5\rangle$

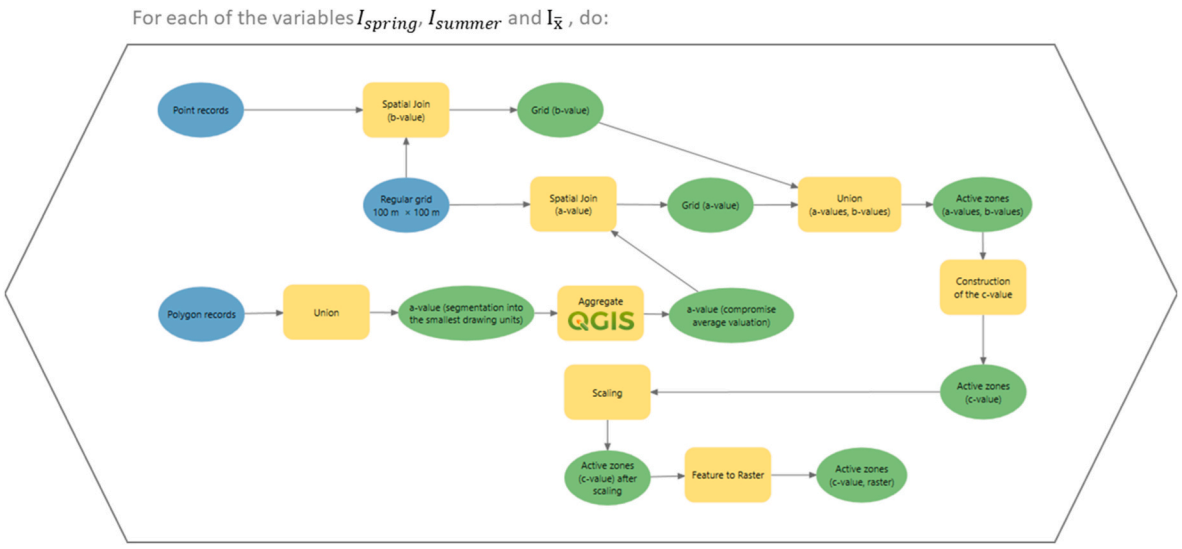


Fig. 4. Simplified diagram of the active zone layers process in GIS environment.

whom were men and 57 of whom were women. Across genders, the most commonly represented age groups were 46–55 (10 female, 17 male), 36–45 (15 female, 10 male respondents), and 26–35 (10 male and 8 female respondents).

As seen in Fig. 5, most of the surveyed population comprised residents living in the specific research area (88%, 93 residents in absolute numbers). The second largest group, but by a significant margin, comprised visitor-tourists (8% share, i.e. 8 respondents). Secondary housing owners and users then occupied a 4% share (4 respondents). Owners and users of secondary housing and tourists comprise 12% of the surveyed population, so this is a negligible sample.

The largest groups of respondents have declared their affiliation with Horka nad Moravou (33 respondents), Příkazy (22), Střeň (18) and Náklo (11). Other municipalities in the specific research area were mentioned by respondents at least once but no more than four times (Olomouc). Seven residents from Hlušovice – a village located outside the specific research area – were recorded as visitors-tourists.

Visitor-tourists most often stated that they visit the specific research area less than three times per month (4 respondents) or 3–6 times per month (2 respondents). See the graph in Fig. 6 for more details. Regarding the purpose of the visit, cycling and in-line (5 respondents) or hiking (3 respondents) predominate.

Out of 105 respondents, 52 responded that they were limited by mosquito activity in the specific research area (equivalent to half of the sample – 50%). Thirty percent of respondents said they were rather limited by mosquito activity. Respondents with predominantly self-limiting feelings (degrees of limiting and rather limiting combined) then occupy 80% of the population and constitute a significant majority. The diagram in Fig. 7 indicates the full structure.

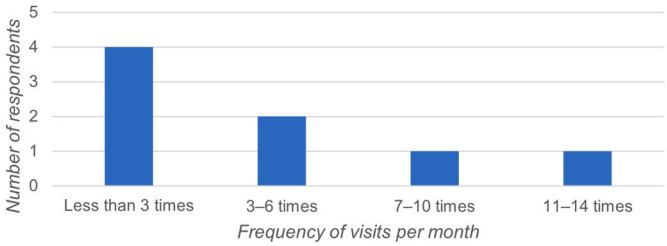


Fig. 6. Frequency of visits by visitors-tourists to the specific research area.

Of the measures listed for mosquito control or elimination (Fig. 8), repellents dominate (78 respondents), followed by contact control at the site of occurrence (12 respondents). Five respondents would choose to cancel a visit/stay in a specific research area and/or reschedule a visit. For the other options offered (limiting the time spent outdoors, using different methods, and not taking action), a negligible number of responses are recorded (4 or less).

The highest number of respondents is inclined to believe that mosquito activity in the specific research area does not change over time in the long term. The other grades are almost equal, with three percent of respondents not venturing to assess the situation. As the graph in Fig. 9 illustrates, nearly 40% of respondents marked the "No Change" option in

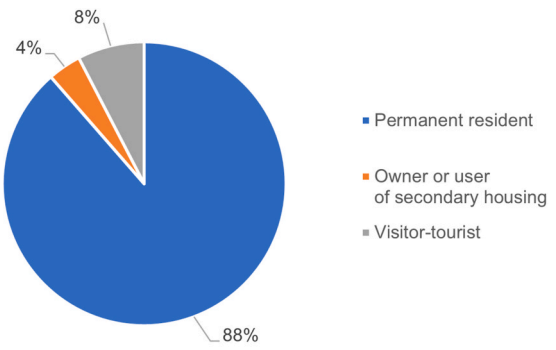


Fig. 5. Respondent structure in relation to the specific research area.

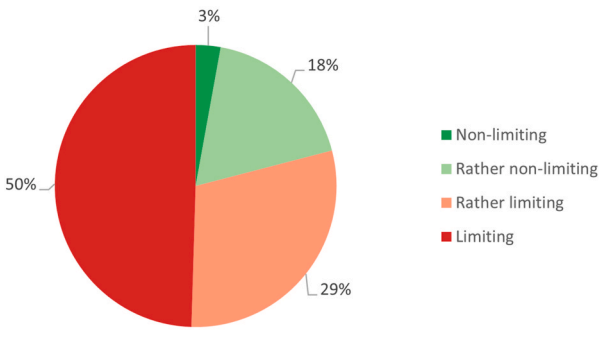


Fig. 7. Mosquito activity and its influence on respondents.

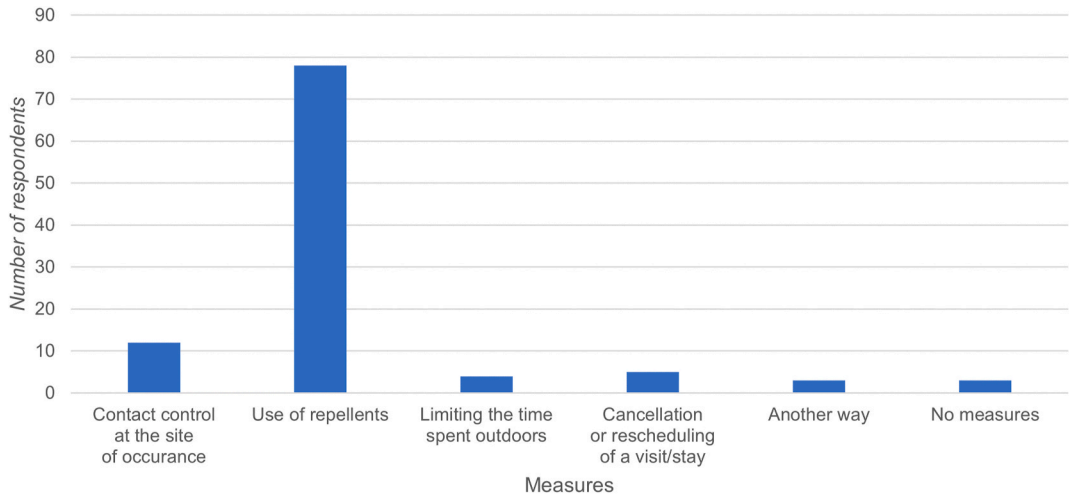


Fig. 8. Measures to reduce or eliminate mosquitoes.

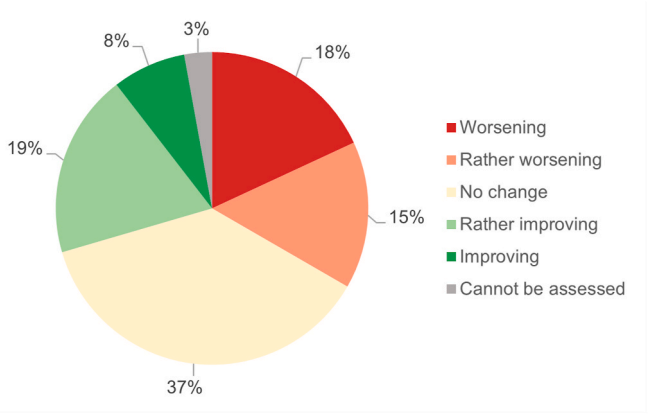


Fig. 9. Mosquito activity and its long-term trend.

the questionnaire. Eighteen percent of respondents believe that the situation is visibly worsening, and fifteen percent lean towards the "Rather worsening" level – a combined 33% share. Approximately 30% of respondents perceive the situation to be improving or rather improving (8% improving, 19% rather improving).

Awareness of mosquito calamity issues (Fig. 10) is insufficient in the specific research area, with more than 50 respondents (i.e., nearly 50% of all respondents) thinking so. Around 30 respondents are fully informed, and 18 receive information on mosquito calamity issues but would like more information.

The most frequently marked places (map in Fig. 11) include the area of the boating camp in Hynkov (part of the Příkazy village), including the immediate surroundings and most of the Horka nad Moravou built-up area on the right bank of the Mlýnský Brook along the border of the protected landscape area. In the northeastern part of the village of Střeň around the Benkovský Brook, a left-side tributary of the Morava River, 8–9 drawings are recorded (the second most numerous category).

The specific research area covers a total area of 465 sq. km (including 93.30 sq. km of the Litovelské Pomoraví PLA), of which the respondents marked 92.53 sq. km as an active area extending both inside and outside the PLA. Based on a combination of the resulting active zone layer and the population grid, the population affected by the respective mosquito activity levels was quantified in Table 6, differentiating between the periods monitored (spring, summer and overall trend).

As Table 6 shows, summer mosquito calamities have a greater impact on the population than spring calamities in terms of area and population numbers. The spring months are dominated by a rather low level of activity, with a total area of about 46 sq. km, affecting nearly 12,000 inhabitants during the day and 4,360 at night. In the months, a high level of activity is the majority, occupying an area of 28.4 sq. km and housing 12,742 and 4217 inhabitants (daytime and nighttime conditions, respectively).

Constructing the overall trend by averaging the spring and summer states together with the 2023 total, it was found that the population most affected during the night state is in high-activity areas (3,456 inhabitants; area 8.06 sq. km). During the daily state, the greatest impact is on the population residing in areas of rather high activity (11,247 inhabitants; 34.91 sq. km).

In the spring months (Fig. 12, top left), rather low-activity areas dominate, occupying more than half of the area. In addition, continuous

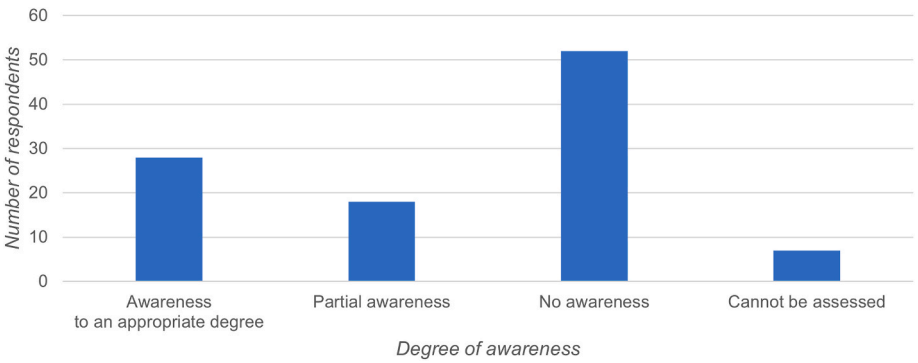


Fig. 10. Awareness of mosquito calamities in specific research area.

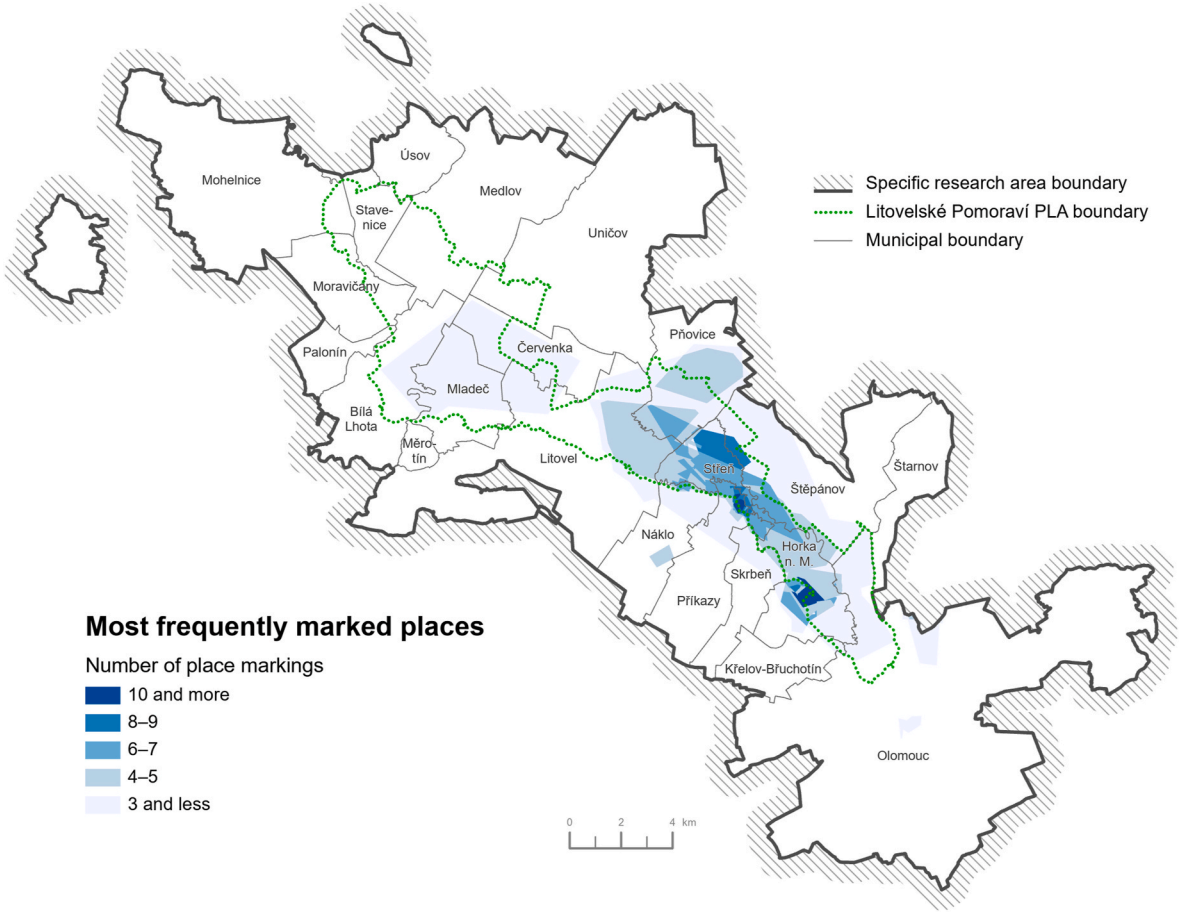


Fig. 11. Most frequently marked places.

Table 6
Activity levels in individual seasons (spring, summer, overall trend) and related areas and population numbers during day and night (highest values of population and areas are orange highlighted).

Activity degree	Spring			Summer			Overall trend normalized by the 2023 state		
	Population		Area (in sq. km)	Population		Area (in sq. km)	Population		Area (in sq. km)
	Daily state	Night state		Daily state	Night state		Daily state	Night state	
High	31	54	2.43	12,742	4,217	28.42	2,715	3,456	8.06
Rather high	2,636	2,886	11.28	1,359	2,490	25.59	11,247	2,024	34.91
Rather low	11,888	4,360	45.50	987	612	10.93	951	40	21.59
Low	102	568	9.15	102	36	2.81	102	2,961	3.81
Not clearly identifiable	2,049	2,972	24.17	2,840	3,485	24.78	1,983	2,359	24.16
Total	**16,706**	**10,840**	**92.53**	**18,030**	**10,840**	**92.52**	**16,999**	**10,840**	**92.53**

bands of rather high activity can be found on the territory of the municipalities of Štěpánov, Horka na Moravě, Střeň and Přovice. High grades can be found only in the minority – in the northern part of Olomouc (in the local part of Chomoutov towards the Chomoutov Lake and the Černovír peat bog) and in Horka nad Moravou.

In the summer months (Fig. 12, top right), there is an obvious increase in active high-level zones in most of the territory of Štěpánov and parts of the territory of Přovice, Skrbeň, Příkazy, Náklo and Litovel – always in the area adjacent to the border of the protected area. Hot spots of the same grade can then be found fragmentarily within the PLA.

In the case of capturing the overall trend (Fig. 12, down), the areas of high activity level are located in the municipalities of Příkazy (northeast

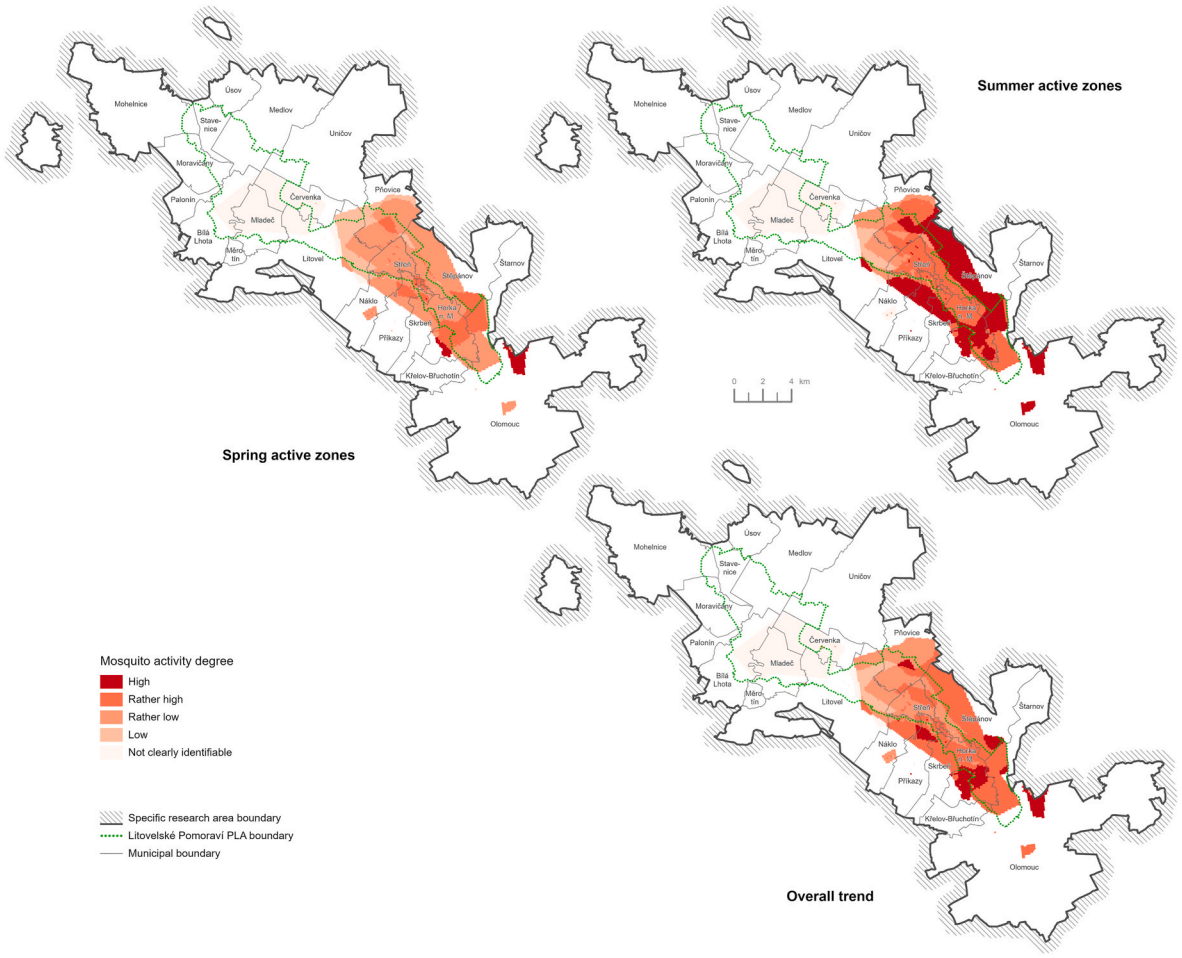


Fig. 12. Spatial distribution of active zones (delineation by respondents' drawing).

of the municipality – local part of Hynkov), Horka nad Moravou (built-up area), Pňovice (Kobylník locality), Štěpánov (area towards Chomoutov Lake) and the northern part of Olomouc (Chomoutov towards Chomoutov Lake and Černovír peat bog). Extensive areas of rather high activity (in relation to areas of rather low activity) are located in the municipalities of Štěpánov, Horka nad Moravou, Náklo, Střeň, Skrbeň and Příkazy – usually at the boundary of the PLA and close to water bodies and streams. According to the respondents, low mosquito activity is typical for the north-western part of the Litovelské Pomoraví PLA, specifically on the Litovel – Pňovice and Litovel – Střeň axes. Areas with ambiguous activity are recorded in the Červenka and Mladeč parts of the municipality.

The existing definition of active zones is burdened by respondents' subjective perceptions, who tend to mark mainly areas in continuously populated spaces where they occur daily (Fig. 12). On the other hand, the objective aspect must also be considered, where the highest activity level is expected in the immediate surroundings of mosquito breeding grounds. Therefore, a new final delineation of the active zones has been made (Fig. 13), which simultaneously considers the data from the questionnaire survey and the location of the mosquito breeding grounds.

An obvious difference from the previous delineation is the shift of areas of high activity from the urbanized parts towards the interior of the integral part of the PLA. In contrast, the adjacent populated parts where direct population contact with mosquito activity is potentially possible have generally decreased one activity level and fragmented continuous areas into smaller units. Outside an integral part of the PLA, high-activity areas have newly emerged in the northern part of the Náklo. The area in the north part of Olomouc remained almost unchanged. Inside the PLA, areas of high activity can be observed in a fragmented manner in the areas of Střeň, Horka nad Moravou and Pňovice.

As seen from Table 7, the largest part of the population is concentrated in areas of rather high activity during the day (2,745 inhabitants) and in areas of medium activity during the night (2,309 inhabitants). The high-activity areas are minimally populated (743 inhabitants in the daytime and 263 at night). The most extensive areas, although not continuous, are the areas of rather high activity, which cover an area of approximately 25 sq. km.

Fig. 14 shows areas of mosquito-threatened populations during the day and night. These areas are spatially delineated and visualized in context with the figural marks of mosquito breeding grounds. In addition to the number of inhabitants in a grid cell, the degree of population threat is also determined by the cell's mosquito active zone.

For the daily state (Fig. 14, left), typical hotspots with high-threatened populations are surrounded by cells with a significantly low-threatened population (workplaces and schools versus empty dwellings with representatives of the post-reproduction group). In contrast, in the night state (Fig. 14, right), an increase in the threatened population (human dwellings) can be observed, which usually forms larger continuous areas. These visualizations intend to highlight, at the level of daily and night population state, the areas with the most threatened populations – i.e., to identify places in the vicinity of which priority measures to improve the quality of life of the inhabitants (e.g. application of larvicides in adjacent mosquito breeding grounds) are necessary rather than to express exactly the population status in each grid cell.

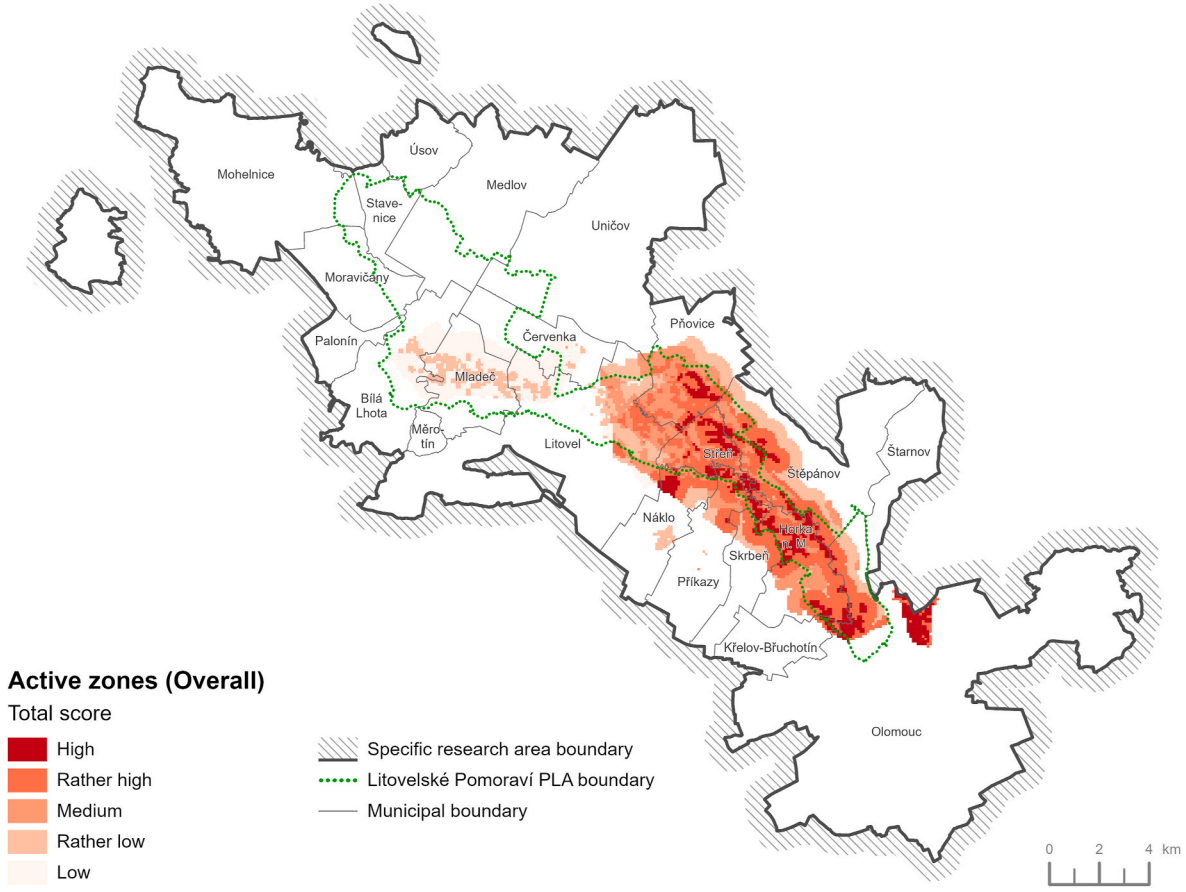


Fig. 13. Overall spatial distribution of active zones (delineation by respondents' drawing and actual breeding grounds locations).

Table 7
Total score categories and corresponding areas and population numbers for daily and night states (highest values of population and areas are orange highlighted).

Total score as a combination of the factors: *distance from the breeding ground, activity level*		**Overall trend** normalized by the 2023 state		
		Population		**Area** (in sq. km)
Category (verbal expression)	**Interval**	Daily state	Night state	
High	⟨10; 15⟩	743	263	9.77
Rather high	⟨6; 10⟩	2,745	2,095	24.83
Medium	⟨4; 6⟩	2,162	2,309	13.68
Rather low	⟨2; 4⟩	1,294	1,347	17.17
Low	⟨1; 2⟩	2,422	3,177	13.35
Total		**9,366**	**9,191**	**78.80**

5. Discussion

A substantial part of the discussion can be conducted on two levels – concerning the layer of population distribution, the subjective aspect of defining the active zones, and the nature of socio-economic research in general.

A fundamental aspect that is not usually taken into account when describing the distribution of the population in an area is the dependence on the time of day – the distribution of the population varies during the day, at night, on weekdays and at weekends. In contrast to traditional approaches (e.g., simply using a permanently living population at the address level), alternative approaches have been used to describe the population distribution during the workday's daytime and nighttime. Implementing the weekend conditions is problematic because the population's behavior depends, among other things, on the tourist attractions and infrastructure of the territory, i.e., the very nature of the territory and other hidden specificities determine it. Their description is complicated because there is no conventional register or dataset to assess it in a standardized way, and it is technically challenging to ensure the actual "counting" of people outside populated

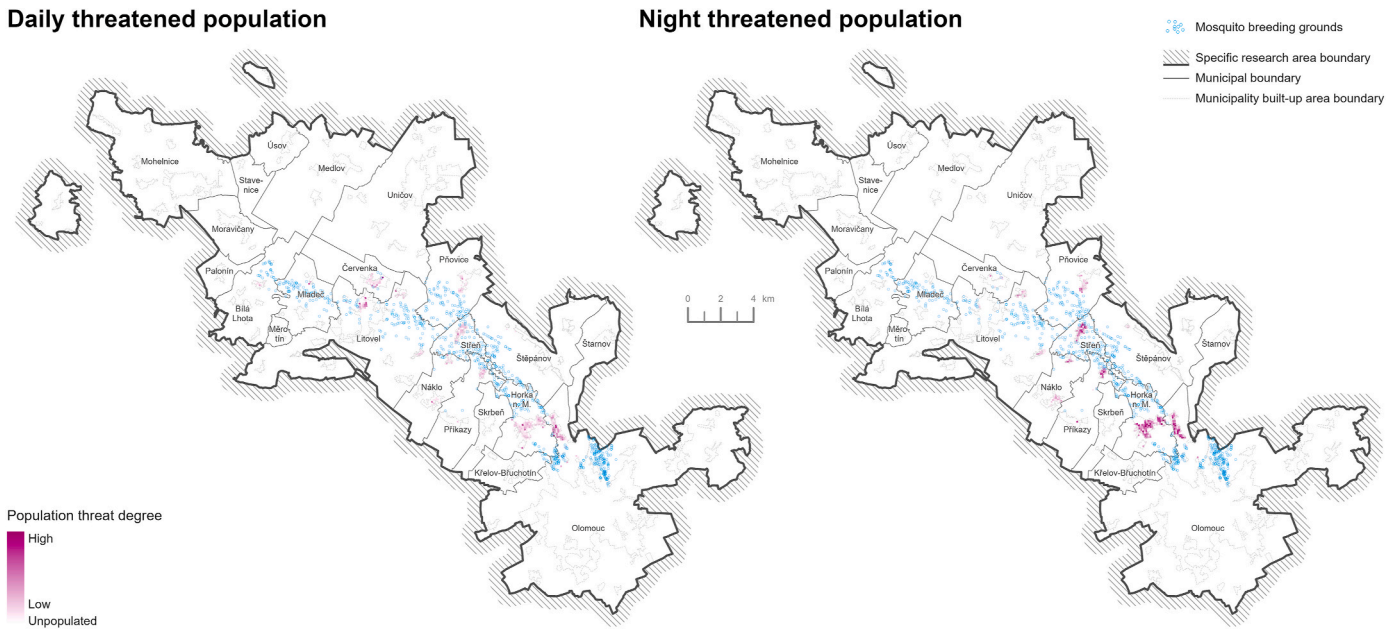


Fig. 14. Spatial distribution of the threatened population during the daily and night state.

areas (Rypl and Burian, 2023).

In the context of the presented representative layer of population distribution, problems related to the input data's lack of detail and uncertainty can be discussed. As already mentioned, a major weakness of the population grid used is represented by the sub-data on the number of workers and employees from the Register of Economic Entities (see Dataset 3 in Table 1), where it is not possible to reliably distinguish between the seat of the entity and its sub-establishments. Therefore, when constructing the population grid, the corresponding value of the number of employees of an entity located in a specific research area, in some cases, included employees from branches/operations located outside this area. This deficiency is compounded by the fact that the data are given only as an interval instead of an exact numerical value. These facts have then caused a steep increase in the values of the daily population distribution, which is most pronounced for large settlements (towns or cities). At the same time, smaller settlements of up to a thousand inhabitants are determined faithfully. Following the authors' original methodology, these weaknesses have been compensated by subtracting the deviation from the corresponding daily population state. Given the absence of a larger number of towns and only the marginal intervention of Olomouc (the largest city in the specific research area/region), this solution is satisfactory. The night-time population figures achieve adequate accuracy. It is important to note that the validation compares usual residence, including foreigners, with the official population estimate based on permanent residence – variations at a reasonable level are thus perfectly natural.

Moreover, the methodology assumes 100% presence of all workers at the workplace at one time, as well as all children and pupils in educational institutions, which is never achieved. Furthermore, it is necessary to note that this figure does not only include the population of the municipality to which it refers but also the population from other municipalities (e.g. in Olomouc – the largest city in a specific research area – people are studying, working, staying in social institutions, and also people from the surrounding area who are not normally counted among the residents), together with from surrounding regions who commute to the specific research area for work.

The questionnaire survey was conducted to obtain information on mosquito activity and its impact on the population, which is undoubtedly burdened with a certain degree of subjectivity. Each respondent has a personal perception, and the idea of what low, rather low, rather high and high mosquito activity means varies slightly across respondents. However, a questionnaire and possibly a personal interview are the only means of gathering and locating information about this phenomenon in space. The survey's subjectivity was considered when defining the active zones – hence the choice of an aggregation function by the mean to compensate for any differences in perceived activity.

Another specificity of the questionnaire survey data is the respondents' natural tendency to mark on the map mainly places in populated parts of the territory, i.e., places where they are in daily contact with mosquitoes. In contrast, there is an objective perspective of the phenomenon, which assumes that theoretically, the highest activity is near mosquito breeding grounds, often located inside protected landscape area far from the built-up areas of villages and towns. Therefore, in the final design of the active zones, both aspects were combined to ensure that the resulting construct reflects the real situation in the area as much as possible.

One can also discuss the stratified distribution of respondents across the municipalities of the specific research area, balanced representation of men and women, equal representation of age categories and categories of respondents according to their relationship to the subject area. Ensuring a complete sample of respondents in human geographic research is often very difficult. Although the respondent base could be considerably broader for some municipalities, the results presented can be considered adequate for the stated research purpose and a true reflection of the actual situation. The ratio of men and women is balanced (women slightly predominate), as is the distribution of age groups across the sexes (though more varied for men). While the predominance of permanent residents makes it impossible to compare the differences in perceptions of activity between groups of respondents, it highlights the perceptions of local people who know the situation in the area best – and can reliably locate, describe and assess it.

For a thorough assessment of the development of the situation, especially concerning climate change, it would be beneficial to repeat the questionnaire survey with a mapping of mosquito calamity hotspots periodically in the coming years, which would allow monitoring changes over time and the development of the overall situation, including verification of the spatial extent of active zones. This would enable a more dynamic understanding of the problem and the development of a more effective long-term management strategy.

The territory is specific in its diversity and number of breeding

grounds. The study was carried out during the prediction and management of the mosquito calamities project, where, in addition to information from citizens living in the area, a range of data about the area was collected, including LIDAR scanning, aerial photography, and installation of sensors in the area. Management without aerial application of products is very limited due to the size of the area and the number of breeding grounds.

Although the survey was carried out in one fixed period, it provides information on the long-term situation in the area. The definition of the active zones itself is based on data from residents who live permanently in the specific research area and know it in detail, which guarantees a faithful representation of the situation on a long-term scale. Therefore, repeating the survey would only make sense if mosquito locations were regularly mapped, which is complicated and time-consuming. It cannot be ruled out that newly mapped breeding sites would again show a certain degree of outdatedness immediately after the mapping was completed. The associated location of the mosquito breeding grounds often varies in the specific study area. Yet, the position relative to the identified hotspots does not change much – the expected variability is on the order of tens to hundreds of meters.

The study was carried out to capture a long-term condition, so it is minimally affected by the actual situation in 2023 when targeted calamity management was carried out. Therefore, the findings and results are adequate and consistent with the stated objectives and the stated concept of integrated management of the area.

6. Conclusion

The paper focused on the novel assessment of mosquito activity and its impact on the population in the territory of the municipalities in the Litovelské Pomoraví PLA. The fulfilment of the set objectives A–D was achieved through three segments – the design and creation of representative population distribution layers, the design and creation of a survey questionnaire, and an overarching segment that integrates the previous two segments and uses them to identify active zones and quantify affected population.

In the segment of **designing and creating a representative population distribution data layer**, a methodology was presented based on the premise of population variability during the day and night as well as on weekdays and weekends. Two variants of the population grid were created using data from Czech national registers – the daily and night states of the working day – because the weekend state is difficult to implement to express the population distribution of the specific research area. Besides visualizing the layers as a grid, the population was quantified at the level of individual villages with specific numbers for day and night. Due to the high overestimation of the daytime population, corrections were made in the form of identifying the average deviation and subtracting it from the corresponding population states.

In the segment of the **design and development of the questionnaire survey segment** implemented to obtain information on mosquito activity and its impact on the population, the requirements were generally formulated, and the structure of the questionnaire and its operation (use) were described. The Pocitové mapy platform (known in English as Emotional Maps) combined a traditional question form and a detailed web map, in which locations can be marked as points and areas.

In the follow-up phase, non-spatial and spatial analysis of the questionnaire data was carried out, culminating in integrating **the outputs of the two previous segments**. Within results evaluation, **which fulfilled objectives A** and **B**, was found, mosquito activity limits residents and visitors to the specific research area. From a long-term perspective, the activity level is neither improving nor worsening, disproving **hypothesis I**. Of the measures cited for mosquito control or elimination, repellents dominate, followed by contact control at the site of occurrence. By integrating population grids describing the distribution of the population in the specific research area and data from the questionnaire survey, the identification of active zones and the quantification of the threatened population was made. This processing procedure was presented both at the level of methodological steps and at the level of technical implementation in the GIS. First, the numerical variables expressing the mosquito activity degree were calculated based on point and polygon data from the questionnaire survey. Then, the data was aggregated by mean and area, which led to the definition of active zones in several variants – spring, summer, and overall.

Regarding the combination of the resulting active zone layer and the population grid, the population affected by the respective mosquito activity levels was quantified, differentiating between the periods monitored (spring, summer and overall trend). This yielded **confirmation of hypothesis II**, as it was found that summer mosquito calamities have a greater impact on the population than spring calamities, both in terms of area and population numbers.

During the spring months, relatively low activity levels prevailed over a total area of about 46 sq. km, affecting nearly 12,000 inhabitants during the day and 4,360 inhabitants at night. In contrast, high activity levels prevailed in the summer, covering an area of 28.4 sq. km and affecting 12,742 and 4,217 inhabitants (day and night, respectively). Based on the construction of the overall trend by averaging the spring and summer conditions together with the 2023 total condition, it was found that the population living in areas with high activity during the night condition would be the most affected (3,456 inhabitants; area 8.06 sq. km). During the day condition, the population living in areas with rather high activity would be the most affected (11,247 inhabitants; area 34.91 sq. km). As well as the population numbers, the spatial extent of the active zones was defined.

Since the active zones defined based on the questionnaire survey data are burdened by the subjectivity of respondents, who tend to identify main areas in continuously inhabited spaces where they occur daily, the objective aspect of assuming the highest activity near mosquito breeding grounds was also considered. This led to a new definition of active zones. An obvious difference from the previous delineation is the shift of areas of high activity from the urbanized parts towards the interior of the integral part of the PLA. In contrast, the adjacent populated parts where direct population contact with mosquito activity is potentially possible have generally decreased one activity level and fragmented continuous areas into smaller units. The largest part of the population is concentrated in areas of rather high activity during the day (2,745 inhabitants) and in areas of medium activity during the night (2,309 inhabitants). The high-activity areas are minimally populated (743 inhabitants in the daytime and 263 at night). The most extensive areas, although not continuous, are the areas of rather high activity, which cover an area of approximately 25 sq. km. **Objective C has thus been met**.

Finally, under **objective D**, mosquito-threatened population areas were identified during the day and night. The threat degree based on the number of inhabitants was also determined again by mosquito activity and distance from breeding grounds. Visualization can be used to visually identify a group of breeding grounds where eradication measures are to be carried out as a priority to improve the quality of life of people in mosquito-threatened populated areas.

The methodology and innovative procedures using geoparticipation and GIS presented are universally valid and can be applied repeatedly, regardless of the specific requirements for the shape and size of the area or the detail of the input data, when dealing with integrated management of the area to map mosquito calamity hotspots, assess the situation and take appropriate steps concerning the environment and in favor of the local population.

CRediT authorship contribution statement

Oldřich Rypl: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Jaroslav Burian:** Writing – review & editing, Visualization, Supervision, Methodology, Formal analysis, Data curation,

Conceptualization. **Jiří Pánek:** Writing – review & editing, Supervision, Data curation. **Jan Brus:** Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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Declaration of competing interest

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

Data availability

Data will be made available on request.

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APPENDIX 4

How Could the Use of Crop Wild Relatives in Breeding Increase the Adaptation of Crops to Marginal Environments?

Renzi, J. P., Coyne, C. J., Berger, J., von Wettberg, E., Nelson, M., Ureta, S., Hernández, F., Smykal, P., & Brus, J. (2022). How could the use of crop wild relatives in breeding increase the adaptation of crops to marginal environments? (vol 13, 886162, 2022). *Frontiers in Plant Science*, 13. https://doi.org/10.3389/fpls.2022.1101822

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How Could the Use of Crop Wild Relatives in Breeding Increase the Adaptation of Crops to Marginal Environments?

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Alongside the use of fertilizer and chemical control of weeds, pests, and diseases modern breeding has been very successful in generating cultivars that have increased agricultural production several fold in favorable environments. These typically homogeneous cultivars (either homozygous inbreds or hybrids derived from inbred parents) are bred under optimal field conditions and perform well when there is sufficient water and nutrients. However, such optimal conditions are rare globally; indeed, a large proportion of arable land could be considered marginal for agricultural production. Marginal agricultural land typically has poor fertility and/or shallow soil depth, is subject to soil erosion, and often occurs in semi-arid or saline environments. Moreover, these marginal environments are expected to expand with ongoing climate change and progressive degradation of soil and water resources globally. Crop wild relatives (CWRs), most often used in breeding as sources of biotic resistance, often also possess traits adapting them to marginal environments. Wild progenitors have been selected over the course of their evolutionary history to maintain their fitness under a diverse range of stresses. Conversely, modern breeding for broad adaptation has reduced genetic diversity and increased genetic vulnerability to biotic and abiotic challenges. There is potential to exploit genetic heterogeneity, as opposed to genetic uniformity, in breeding for the utilization of marginal lands. This review discusses the adaptive traits that could improve the performance of cultivars in marginal environments and breeding strategies to deploy them.

Keywords: abiotic stress, adaptation, breeding, crop wild relatives, legumes, marginal environment

INTRODUCTION

When coupled with the use of irrigation, fertilizers and pesticides, modern breeding has increased agricultural production several fold in favorable environments (Evenson and Gollin, 2003). However, such high-input agriculture also has a high environmental impact. High performing

cultivars are designed under good field conditions and perform well when there is sufficient water and nutrients, e.g., fertile soil. However, such conditions are often not available because there is a large proportion of arable land in marginal environments globally (Sebby, 2010; Pingali, 2012). Marginal land exists worldwide (e.g., Kang et al., 2013), and typically, it is of poor soil fertility. In many areas these soils are prone to erosion, with shallow soil layers, and may be prone to drought, salinity, or other abiotic challenges. Moreover, these environments are expected to expand with ongoing climate change and increasing degradation of soil and water resources (El-Beltagy and Madkour, 2012).

Throughout evolutionary history, plants have had to adapt to a range of environmental conditions including adverse habitats. As a consequence, plant species including crop wild relatives typically exhibit a high level of genetic and phenotypic variation within their distribution range (Anderson et al., 2011; Russell et al., 2014; Smýkal et al., 2017; Hellwig et al., 2021). Understanding the genetic, biological and ecological bases of local adaptation is relevant to manage the impact of climate change on crop and animal production. In widely distributed plant species inhabiting different environments, ecotypic differentiation has been detected for populations along altitudinal, latitudinal or environmental gradients (e.g., Polechová and Barton, 2015; Berger et al., 2017). Understanding the extent to which such distinct ecotypes are formed will help not only to reveal and recognize their evolutionary adaptive patterns, but also will help breeders to use their diversity to maximize productivity under target environments.

It is widely accepted that past domestication processes have resulted in a narrower genetic base of cultivated germplasm that is prone to pests and diseases (Tanksley and McCouch, 1997; McCouch et al., 2020; Khoury et al., 2022). Unlike their domesticated crops, crop wild relatives (CWRs) continued to evolve to adapt to their environments and thus provide a key resource to counteract the effects of climate change on the world's food supply. To fully understand and utilize this process, studies in the geographical centers of origin are needed combining ecology, physiology and genetics. This approach was pioneered by N.I. Vavilov in the 1920s–1930s starting with surveys, collecting missions and subsequent evaluation of germplasm collections in diverse environmental settings (Vavilov, 1957). Today, with the available tools of genomics, geospatial analysis and modeling combined with improved phenotyping methods, it has become all the more important to analyze wild accessions and use them as sources of stress tolerance for breeding purposes (Warschefsky et al., 2014; Coyne et al., 2020). Wild species have been used mainly for the introgression of disease and insect resistance into crops (e.g., Hajjar and Hodgkin, 2007); drought, cold, heat and salinity tolerance have also been addressed in some staple crops (Prohens et al., 2017). Biotic and abiotic stress resistances have been explored in wild relatives of many crops including chickpea, barley and maize (Brozynska et al., 2016; Fustier et al., 2017; von Wettberg et al., 2018; Liu et al., 2020). A complementary approach is the *de novo* domestication of new crops (Smýkal et al., 2018; Fernie and Yan, 2019).

Environmental fluctuations such as soil salinity, cold and drought stress represent a major constraint on agricultural productivity. Water availability and temperature extremes are the major factors controlling the distribution of vegetation over the earth's surface. Crop yields are more dependent on an adequate supply of water than on any other single factor; environmental stress represents the primary cause of crop losses. With current climate change projections, extremely hot weather will become more frequent and rainfall will be more erratic in many regions of the world (Foyer et al., 2016). As many elite cultivars tend to be drought sensitive, ensuring food security will require development of more drought resistant varieties. Dissection of adaptation mechanisms to harsh conditions naturally occurring in wild relatives of domesticated crops may provide a solid foundation for crop improvement under the changing climate. Drought and heat stresses impact every plant developmental stage, starting from seed germination, through vegetative growth. However, the most adverse effects (from a crop production perspective) are on crop establishment (germination and young seedling phase) and reproduction, which are very sensitive to suboptimal conditions. Small seedlings and pollen grains happen to be particularly sensitive to lack of water and excess heat (Dürr et al., 2015; Yu et al., 2019; Chaturvedi et al., 2021; Chen et al., 2021).

MARGINAL ENVIRONMENTS AND THE IMPACT OF CLIMATE CHANGE

The term "marginal" land originated in the field of agricultural economics during the 19th century (Kang et al., 2013) by Ricardo (2005) using the categorization from his land rent theory which was the basis of marginal productivity theory. Marginal lands are subject to socio-economic and biophysical constraints, and lower productivity. Nevertheless, it is difficult to define "productivity" within this concept because this varies depending on land use. For example, land that is too marginal for crop production might be suitable for grazing, and "fragile" land can be susceptible to soil degradation, but it may still be suitable for sustainable forestry. Many dry-land countries have not assessed the extent or characteristics of these lands, nor their sustainability as biofuels or food crops production. These lands are often difficult to exploit economically and sustainably for agriculture, and can lead to abandonment (Campbell et al., 2008). Land can also be degraded due to an intensive and unsustainable use (Campbell et al., 2008; Dauber et al., 2010). Marginal lands are areas with low rainfall, high temperatures, low quality soils, steep terrain, shallow soil depth (less than 50 cm), poor fertility, coarse texture, stony, heavy cracked clays, salt-affected lands, waterlogged, marshy land, barren and rocky soils, and other problems. If a land is considered marginal it means that it does not have enough capacity to produce food, or other agricultural activities.

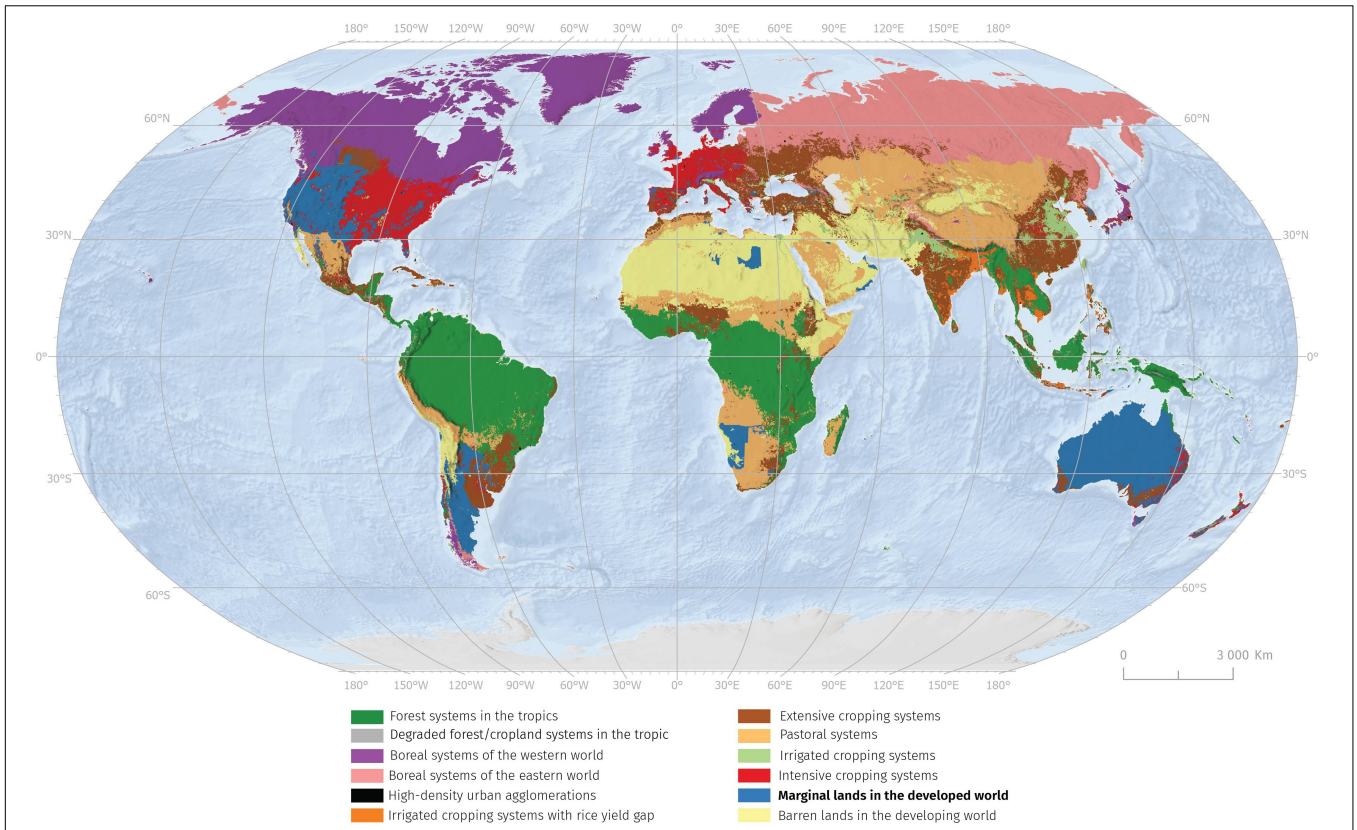


FIGURE 1 | Map shows global land system archetypes classification by Václavík et al. (2013). Within the global scale, marginal lands in the developed world cover about 9% of terrestrial ecosystems.

Nearly one billion people live in poverty today, a high percentage living in these marginal lands in mostly developing countries (Ahmadzai et al., 2021). These areas with low soil fertility and limited agricultural value are also highly vulnerable to climate change (Castro and Castro, 2019). The research concluded that in total 29% of the agricultural area is marginal in European Union. The most common reason is the rooting limitations; 12% of Europe's agricultural area required intervention to improve soil structure and depth to allow farming. This is followed by adverse climate and excessive soil moisture occurring in respectively 11 and 8% of the agricultural land (Elbersen et al., 2018). Within the global scale marginal lands in developed world covers about 9% of terrestrial ecosystems (Václavík et al., 2013). These lands occur predominantly in Western United States, Australia, Argentina, but also in North and South Africa (**Figure 1**). A more precise estimation of area covered by marginal lands is limited by uncertainties and problems of land cover classification (Brus et al., 2018). Marginal lands are most vulnerable to climate events like drought and floods, thus, most likely to be affected by climate change. Climate change has made it difficult to maintain established farming practices in recent decades. Within the US the prevalence of local yield deficits confirms that individual farmers looking to expand their operations are generally confined to cultivating increasingly marginal land, though widespread variation exists from location to location (Lark et al., 2020).

The effects of climate change are manifested as erratic precipitation and weather changes, which have led to rapid fluctuations and unpredictable temperatures. Adaptation to this requires new approaches to agriculture. For example, research on agro-climatic conditions has shown that farmers in dryland areas are more aware of climate change impacts than those in wetland areas. Similar findings have also been reported for Ecuador (Skarbø and VanderMolen, 2014). It is unclear, however, if agricultural producers can keep up with climate change at the incredible pace it is predicted to occur in coming years (Jones et al., 2012). Adaptation to climate change is difficult and impacts are based on various assumptions. In addition to estimating future impacts, researchers need to make subjective value judgments. This is especially true of social and economic development in marginal regions. As a result, the effects of climate change on these areas are difficult to forecast. Although the impacts of climate change are not always measurable, they are still a huge concern for governments and local communities alike. Some areas of the world are particularly vulnerable, and these risks can be mitigated by developing new approaches and technologies in crop production. One such approach is the implementation of

local and regional adaptation plans. However, it is crucial to consider the broader context of marginal environments when developing policies and adaptation strategies for agricultural producers. This research is particularly important in Latin America, where smallholder farmers are heavily impacted by climate change. Moreover, rural and subsistence farming are often location-specific systems, which are highly vulnerable to the stressors of the climate. As a result, the research needs to take this into account. Agro-ecosystems are critical for food production and sustainability, but they are also prone to pests. Consequently, many current crop varieties will have to be replaced as a result of climate change. Failure to address these challenges will have a profound impact on the global economy and on social well-being. If we fail to protect and restore natural ecosystems, it will become impossible to grow crops in these marginal areas in the future. One of the possible way how to cope with this situation is implementation of Climate-Smart Agriculture (CSA) (Lipper et al., 2014).

CONTEXT: HOW AND WHY DO CROPS AND THEIR WILD RELATIVES DIFFER?

Crop wild relatives typically harbor far greater genetic diversity than modern elite crops as a result of primary and secondary domestication bottlenecks; the founder effect(s) and subsequent fixation of domestication syndrome and post-domestication traits including cultural selection for local preference (Tanksley and McCouch, 1997; Purugganan and Fuller, 2009). Moreover, the evolutionary trajectory and resultant selection pressures encountered by wild progenitors and elite cultivars are very different. While we can now deploy an impressive array of technical and analytical approaches for handling complexity in the search for adaptive genes (Cortes and Lopez-Hernandez, 2021), here we argue that understanding the divergent selection pressures encountered by wild progenitor and elite cultivar adds invaluable context for the use of CWR in improving crop adaptation.

Wild progenitors are subject to natural selection in response to environmental stressors, herbivory, pathogen attack and inter-plant competition from the same or other species occupying similar ecological niches in a variable climate. While viable seed production is the ultimate measure of 'fitness,' reproductive investment in CWR is usually lower than in their domesticated counterparts (Berger et al., 2017; Berger J. et al., 2020; Garibaldi et al., 2021). This implies that competition for resources such as light, nutrients or water is selecting for greater vegetative investment (roots, shoots, leaves) in CWR relative to the domesticated crop, akin to the competitors in Grime's triangle (Grime, 1974). In some examples the genomic consequences of this divergent selection for reproductive versus vegetative investment have been identified, such as the selection for increased apical dominance (e.g., reduced branching) in the domestication of maize (Clark et al., 2004). Seed dormancy, a key domestication syndrome trait, can both exacerbate and ameliorate seasonal variability in CWR. In many Mediterranean CWR seed physical dormancy has been selected as bet-hedging against false breaks (heavy rainfall that precedes the growing season start and which would expose the recently germinated seedling to extreme heat and drought) and other disturbances such as catastrophic herbivory (Piano et al., 1996; Norman et al., 2002; Smýkal et al., 2014; Berger et al., 2017). Typically, there is wide ranging dormancy within populations (Berger et al., 2017; Hradilová et al., 2019; Renzi et al., 2019), that in combination with variable seed placement will drive staggered germination across the CWR population over the growing season, exposing individuals to different micro-habitats in space and time.

Conversely, crop plants are subject to a combination of natural and artificial selection giving rise to the domestication syndrome (large seed size, loss of dormancy, and seed dehiscence etc.) and subsequent selection for local adaptation and food preferences (Fuller and Allaby, 2009; Purugganan and Fuller, 2009; Smýkal et al., 2018). Compared to CWR, modern crops lead a strictly regulated life in a tightly defined growing season. Non-dormant seeds are accurately positioned with respect to soil depth and neighbor distance in a prepared seedbed during an optimal window, matching phenology to target environment to minimize frost, drought, and other stress. Ripening is both uniform and timely because of the use of determinate cultivars (e.g., cereals), selection for earliness (e.g., chickpea, lupin, canola), or the application of desiccants (e.g., canola, chickpea). Herbivory and diseases are minimized by management interventions. Importantly, crops are selected on the basis of communal, rather than individual yield, whereas the opposite is the case for CWR. As a result, modern crops tend to be weak-moderate competitors (Donald, 1981; Weiner et al., 2017) with a greater reproductive investment than their wild progenitors (Berger et al., 2017; Berger J. et al., 2020; Garibaldi et al., 2021).

Finally, domestication and subsequent global dispersal further widens the evolutionary dichotomy between crop and CWR (Purugganan and Fuller, 2009). Chickpea represents an extreme exemplar, having been domesticated from a very narrowly distributed southeastern Anatolian wild progenitor with a Mediterranean winter annual lifecycle into a global crop grown on all continents except Antarctica. It has been hypothesized to have returned to the Mediterranean as a spring-sown late season crop after a 2000 years archeological gap (Abbo et al., 2003). The much more recently domesticated narrow-leafed lupin (*L. angustifolius*) and yellow lupin (*L. luteus*) represent the opposite extreme. Here the wild progenitors range widely around the Mediterranean basin (particularly *L. angustifolius*), being domesticated in the 18th century as spring-sown crops for limited sandy acid soil regions in central and eastern Europe (Hondelmann, 1984), and then returning to Mediterranean climates in the southern hemisphere in the last 50 years (Gladstones, 1994). The combination of divergent genetic diversity and evolutionary trajectory/selection pressures leads to different adaptive traits in crops and their wild relatives.

The regulation of phenology in Mediterranean crops and wild relatives provides clear examples of divergent evolutionary paths. For example, vernalization plays an important role in regulating phenology in both wild *Cicer* and *Lupinus*, presumably as a consequence of the cool-cold winters and rapidly warming spring temperatures experienced in their Mediterranean distribution range. Wild narrow-leafed and yellow lupins are widespread species in which flowering time and associated traits including water use, biomass production and reproductive investment are strongly linked to rainfall at origin (Berger and Ludwig, 2014; Berger et al., 2017; Berger J. D. et al., 2020). Despite the importance of phenology in ecotypic adaptation of wild lupins, there is very little variation in vernalization response (Taylor et al., 2019). Similarly, most wild *Cicer* species also appear to be consistently vernalization responsive (Berger et al., 2005), suggesting that other regulatory mechanisms such as photoperiod or temperature responses or earliness *per se* are responsible for the phenological differences observed across wild germplasm collections. Indeed, wild *Cicer* species appear to be extremely photoperiod responsive (Sharma and Upadhyaya, 2019) and investigations are ongoing to reveal interactions between all three phenology regulators (vernalization, photoperiod, temperature) in order to understand the regulation of flowering time and what CWRs might bring to the crop.

Conversely, downregulation of the vernalization response has played a key role in the domestication of chickpea and both lupin species as these crops moved away from their cool-cold winter Mediterranean origins. Selection for earliness and high early vigor were key breeding criteria in both lupin species in their domestication as spring-sown crops because timely maturity in the cooling late central-eastern European summer was essential to reliable seed production (Hondelmann, 1984). When the crops moved to relatively warm-winter Mediterranean climates in Australia, where vernalization is a mostly unreliable regulator of phenology, it was necessary to identify unresponsive mutants to start the industry effectively (Gladstones and Hill, 1969). Now, both Australian and European Lupin breeding is dominated by the vernalization unresponsive *FT* alleles (Taylor et al., 2019, 2021). In chickpea vernalization was presumably downregulated in the Bronze Age introduction of the crop to South Asia and its hypothesized return as a Mediterranean spring-sown crop (Abbo et al., 2002, 2003; Redden and Berger, 2007). Unlike lupin, the much older chickpea crop has formed distinct ecotypes with different flowering regulatory mechanisms appropriate to each region (Berger et al., 2011). Thus, chickpea landraces become increasingly temperature responsive from the Mediterranean through north, central and southern India, temperature response being strongly correlated to collection site temperature during the vegetative phase (Berger et al., 2011). Among Eastern Mediterranean germplasm photoperiod and temperature response were negatively correlated, a relationship that is likely to have been essential in the colonization of warmer climates in South Asia where a strong photoperiod responsive is maladaptive, particularly in Southern India where chickpea flowers under declining day length.

Divergence in adaptive strategies between crops and wild relatives provides opportunities to modify crop adaptation to new and marginal environments, while understanding which traits are selected for what regions adds useful context to the problem. For example, genes from chickpea wild relatives would be invaluable in the creation of a winter cultivar because these appear to have been lost in evolution of the crop. Indeed, chickpea wild relatives are more winter hardy than domesticated chickpea (Singh et al., 1990, 1994) and appear to have greater reproductive chilling tolerance as well (Berger et al., 2012b). Efforts are currently underway to improve cold tolerance in chickpea using wild relatives. In narrow-leafed lupin the strong selection for earliness has created a bottleneck which is limiting yield potential in higher rainfall environments where longer season cultivars will be better adapted (Berger et al., 2012a; Chen et al., 2017). As a result, considerable effort is being invested in the search for other regulatory levers with which to delay flowering in lupin without re-introducing an obligatory vernalization requirement (Taylor et al., 2019, 2021). Wild germplasm is playing an important role in this. These examples stand out because phenology has played such a central role in the divergent evolution of crop and wild relative in both chickpea and lupin.

When the differences between crop and wild relative are more obscure, it becomes more difficult to generalize about the adaptive potential that may be exploited from CWR. Drought stress often occurs in marginal environments as described earlier. Among annual plants the principal adaptation strategy is stress avoidance through appropriate phenology, with some very limited capacity for drought postponement through water acquisition (e.g., deep roots) and conservative water use (e.g., stomatal closure), and very short-term tolerance through osmotic adjustment (Ludlow and Muchow, 1990; Berger et al., 2016). Given the widespread selection for earliness in domesticated crops compared to their wild relatives, it is difficult to argue that CWR will improve the capacity for drought avoidance in our crops. However, CWR may be a useful source of drought postponement or tolerance traits, given that these are likely to be under selection in wild populations where individuals compete amongst themselves and often also have long, indeterminate lifecycles which include periods of transient drought stress (Berger et al., 2016). Lysimetry has demonstrated that the wild *Cicer* species, *C. echinospermum* and *C. reticulatum* extract more water both under terminal drought and well-watered conditions than does domestic chickpea (Berger J. et al., 2020). At this stage the underlying mechanism is unknown. If the greater water use extraction of wild *Cicer* is explained by greater vegetative investment and associated lower water-use efficiency, it will be maladaptive in the chickpea crop; if it represents a capacity to tolerate lower water potential, however, it may be useful. Wild *L. luteus* has a greater capacity to maintain leaf water content at low water potential than the domesticated crop, probably through osmotic adjustment (Berger and Ludwig, 2014; Berger J. D. et al., 2020). Surprisingly this capacity was only found in high, rather than low rainfall ecotypes and was suggested as a bet-hedging strategy to postpone self-induced transient drought caused by very high water-use of high rainfall ecotypes.

Currently, there are not enough ecophysiological studies of annual adaptive strategies over contrasting climates to generalize about the likelihood of finding these sorts of adaptive traits among CWR. There has been no evidence for similar drought stress tolerance on low and high rainfall ecotypes of wild *L. angustifolius* (Berger J. D. et al., 2020), Conversely Yousfi et al. (2010) detected greater osmotic adjustment capacity in low compared to high rainfall ecotypes of *Medicago truncatula* and *M. laciniata*. We hope that future germplasm screening efforts used in crop improvement will address this shortcoming by studying material from contrasting, well characterized collection sites.

DESIRABLE CROP WILD RELATIVES PHENOTYPIC TRAITS TO IMPROVE CROP ADAPTATION TO MARGINAL ENVIRONMENTS

Selection attributes according to the crop objective are related to classical domestication traits, such as reduced seed and fruit dispersal, changes in plant structure, plant phenology, seed dormancy, palatability, or acquisition of modified fruit size and shape in vegetable crops (Alonso-Blanco et al., 2009; Sakuma et al., 2011; Meyer et al., 2012; Zohary et al., 2012; Abbo et al., 2014; Fuller and Allaby, 2018; Ogutcen et al., 2018; Smýkal et al., 2018; Iqbal et al., 2020). Much progress has been made in the most widely grown and intensively selected crops (rice, wheat, soybean, sugarcane, tomato and potato), but improvement using CWR is more recently (Hajjar and Hodgkin, 2007; Shelef et al., 2017; Zhang et al., 2018; Zsögön et al., 2018; Fernie and Yan, 2019). CWRs provide unique reservoirs of genetic diversity for crop improvement (Cowling et al., 2009; Redden, 2013; Matesanz et al., 2020; Bohra et al., 2021). They have typically been used in breeding to introgress a small number of major genes (for insect/disease-resistant varieties), in contrast to adaptation that is controlled by many small-effect quantitative trait loci and complex interactions which are more difficult to harness (Hajjar and Hodgkin, 2007; Zhang et al., 2018; Zsögön et al., 2018). The introgression of adaptive diversity from CWR to domesticated crops provides breeders with new tools for crop improvement (Smýkal et al., 2018). As environmental changes associated with domestication should favor resource-acquisition strategies compared with the resource-conservation strategies of wild relatives (Redden, 2013; von Wettberg et al., 2014; Vilela and González-Paleo, 2015), breeders are faced with the challenge of a trade-off between productivity and adaptation. The development of a variety with high adaptation (survival) under a marginal environment, but very low productivity would not be desirable (Richards, 2006; Berger et al., 2016).

Cultivars with tolerance to drought, heat, salinity, soils with extreme pH (alkaline or acidic) and low fertility, as well as various biotic factors are known to be required in marginal environments (Redden, 2013; Quezada-Martinez et al., 2021). Irrespective of the pre-breeding technique it is important to understand the phenotypic traits that confer adaptation for identification in any given marginal environment and for agronomic management (Wilke and Snapp, 2008). Appropriate phenotypic traits (morphological, anatomical, and phenological) that are easily distinguishable and inexpensive to measure in the field, suitable for pre-breeding programs in developing countries, where marginal environments predominate, could be considered. However, the breeding efficiency might be low (Araus and Kefauver, 2018). On the contrary, adaptation to salinity through the evaluation of osmoprotectants, reactive oxygen scavengers (ROS), stress proteins and ion/proton transporters, or the resistance to diseases-pests not strongly associated with specific phenotypic traits, requires more complex screening and modern techniques (Araújo et al., 2015). Since many CWR can help stabilize and increase productivity in marginal agroecosystems, the phenotypic traits that provide these and other types of services of candidates for domestication should be described. **Table 1** presents some phenotypic traits that are related to the plant responses to marginal environmental factors. These traits can guide breeders who are seeking new germplasm for domestication.

Note that some traits are not directly related to yield, or even appear to be indirectly associated, but will favor adaptation in a marginal environment in the long term (Duc et al., 2015; Vilela and González-Paleo, 2015). For example, it is known that the use of high reproductive biomass (high harvest index) as a key selection criterion leads to increased wheat yield (Reynolds et al., 2007). However, in marginal environments in the northern Patagonian region of Argentina, it may be preferable to select high plant height and late-cycle wheat to cope with transient stress while maintaining the yield ceiling ($\sim$ 1–1.5 t ha^{-1}). Tall crops could favor competition with weeds, and the late-season genotype could prolong the duration of root growth, allowing the utilization of water and nutrients deeper in the soil profile (Richards, 2006). In addition, higher post-harvest residues with firmer stubble could increase soil cover, favoring soil moisture retention and avoid erosion processes that frequently occur in bare soils (Silenzi et al., 2012). Often remnant vegetative biomass is used as forage or for fuel. This is one of the reasons why traditional local varieties are still used instead of modern ones in this marginal environment (Cantamutto et al., 2016). In the case of forage legumes, the simple selection of a major trait (biomass) with four adaptive traits was useful for improving a semi-domesticated species such as hairy vetch (*Vicia villosa*) (**Figure 2**). The adaptive traits were late phenology, aboveground morphology (high plant branching), dense leaf pubescence and high seed dormancy. The long period of vegetative production was associated with the ability to modify the growth and flowering phases according to the occurrence of rainfall events. Successful adoption by farmers has occurred with the cultivar Patagonia INTA, with a high biomass and regrowth capacity after grazing, tolerance to transient drought, resistance to cold, and adequate natural reseeding (Renzi, 2020). The lesson is that adaptive traits have to be considered with the target environment *and* end user in mind; seed yield may not always be the dominant criterion.

TABLE 1 | Linking phenotypic traits and adaptation strategies that could be used as pre-breeding criteria in a population improvement program in grain and pasture crops.

Specific adaptation strategy	Phenotypic trait of interest	Target environment	References
Drought escape.	High seed size. Rapid germination and growth rates (high seedling vigor).		Thomson and Siddique, 1997; Berger et al., 2002, 2016; Richards, 2006; Reynolds et al., 2007; Sadras and Richards, 2014; Araújo et al., 2015; Duc et al., 2015; Gardarin et al., 2016
The life cycle is completed before a severe water deficit develops.	Early flowering and physiological maturity phenology. Determinate growth habit. High specific leaf area (SLA). Stay-green. Dry matter remobilization and high reproductive investment (harvest index). Lengthened seed-filling period.	Terminal drought (or *end-of-season drought*)	
Drought avoidance/postponement. *When maximizing water uptake and/or reduced soil water depletion.*	Phenology adjustment (*ability to modify growth and flowering phases according to occurrence of rainfall events*). Root:shoot ratio increase. Leaf area reduction. Leaf thickness increase. SLA* reduction. Leaf senescence delay. Leaf movement (paraheliotropic, rolling). Leaf (canopy) temperature reduction.	Transient stress (or *droughts occurring at any time of the growing season*)	Berger et al., 2002, 2016; Richards, 2006; Reynolds et al., 2007; Wilke and Snapp, 2008; Fernández et al., 2012
Drought and temperature stress tolerance. *Specific adaptation to water deficit through organs or processes.*	Dense leaf pubescence. Smaller and thicker leaf. High thick leaf cuticle. High leaf wax. Low SLA*. Deep root. High root:shoot ratio. Green photosynthetic organs other than leaf (stems on shrubs, beard in cereals). Nyctinastic leaf movements. Leaves highly reflective or orientated at steep angles.	Transient and terminal drought	Sandquist and Ehleringer, 1997; Passioura, 2006; Richards, 2006; Reynolds et al., 2007; De Andrés et al., 2008; Wilke and Snapp, 2008; Araújo et al., 2015; Vilela and González-Paleo, 2015; De la Rosa et al., 2020
Weed competitiveness	Low seed dormancy Rapid growth rates. High plant height. High specific leaf area. Dense leaf canopies. Spread root systems. High tillers/stems per plant. High dry matter.	Mild, transient stress	Hoad et al., 2006; Duc et al., 2015; Gardarin et al., 2016
Winter survival	Survival testing (at $< 0°C$) Median lethal temperature (LT_{50}) Regrowth ability after freezing Pubescence	Freezing winter	Badaruddin and Meyer, 2001; Brandsæter et al., 2002; Wilke and Snapp, 2008; Araújo et al., 2015; Wiering et al., 2018
Prevents germination in unfavorable conditions	Seed dormancy High seedling growth rate	Initial drought	Loi et al., 2005; Norman et al., 2005; Gardarin et al., 2016
Ability to recover from transient damage (grazing, predation and biotic stress)	Hypogeal emergence. Phenology plasticity (*to extend the growing season*). Secondary stem/shoot production. Indeterminate growth habit. High allocation to roots or storage organs. Low HI or RE (reproductive effort). Deep-rooting.	Grassland – Pasture crop	Wilke and Snapp, 2008; Annicchiarico et al., 2015; Araújo et al., 2015; Duc et al., 2015; Renzi, 2020

**Specific leaf area (SLA) = leaf surface area (cm^2)/leaf dry mass (g).*



FIGURE 2 | Seed collection **(A)**, plant breeding **(B)**, multiplication **(C)**, and agronomic use **(D)** of the improved cultivar of hairy vetch (*Vicia villosa*) cv. Patagonia INTA as forage and cover crop.

A less common but promising approach is the domestication of perennial grain crops. Traditional systems relying on annual crops have substantial negative impacts on ecosystem functions (i.e., nutrient cycling, water quality and carbon emissions, salinity, soil erosion and degradation) (Tilman et al., 2011). These problems can be reduced through the introduction of perennial crops in some environments (González-Paleo and Ravetta, 2015). This is illustrated by perennial Silphium oilseed (Heliantheae), with ideotypes with desirable traits for improving long-term yields and ecosystem services (Runck et al., 2014; Van Tassel et al., 2017). Kernza, a large-grained variety of intermediate wheatgrass (*Thinopyrum intermedium*) (DeHaan et al., 2020), is similar. The introduction of greater diversity in cropping systems through biotypes for mixed cultivation ("ideomixes"), with high resource-use complementarity, is also used as a novel approach by breeders (Litrico and Violle, 2015). For forage purposes, the domestication of shrub-tree legumes for livestock production has the potential not only to enhance productivity, but it could also provide multiple environmental benefits, such as providing shade for cattle, restoring degraded lands and mitigating greenhouse gas (GHG) emissions (Muir et al., 2018). The concept of the traditional ideotype in marginal environments needs to be discussed, and the ecosystem services of these should be considered (Duc et al., 2015). While introduction of perennial crops may not suit every marginal environment (such as those that experience extended hot and dry summer seasons), more research effort should be directed toward exploring the potential fit of perennial crops to different marginal environments.

Different drought scenarios (opportunity, extent, intensity and frequency of drought) and heat-stress are the most common and important stress factors in marginal lands (Chapman et al., 2000; Reynolds et al., 2007; Berger et al., 2016; Sehgal et al., 2018). This combination of changes in temperature and rainfall patterns is driving the development of drought-adapted crops. **Table 1** details the different adaptive strategies to drought and the associated phenotypic traits; however, the integration of traits into an adaptive strategy that explains how species or genotypes address drought stress should be analyzed in a specific context that considers environmental selection pressures.

The phenotypic traits between drought postponement and tolerance may be overlapping in the same directions (co-gradient variation). Plant adjustments under stress conditions (plasticity) as opposed to tolerance as a constitutive trait of the species independent of water and/or heat stress are considered. Both the genetic differentiation in phenotypic traits and the plasticity of those traits are complementary mechanisms contributing to plant adaptation to environmental resource fluctuation (Matesanz et al., 2020). Uniform-rich habitats or consistently stressful environments (homogeneous and predictable low-resource environments) promote genetic differentiation rather than plasticity. On the contrary, unpredictable environments can lead to increased phenotypic

plasticity (Vilela and González-Paleo, 2015; Espeland et al., 2018). Thus, the plasticity could represent most of the phenotype variation in some traits (phenology, leaf morphology) when compared with the genetic contribution; it has been suggested that it could be beneficial under climate change scenarios (Nicotra et al., 2010). In order to detect "plastic ideotypes" and exploit the plasticity in pre-breeding programs, a wide range of environments in order to fit models of phenotype versus environment should be included (de Felipe and Alvarez Prado, 2021).

In this context, CWR show high genetic variation for adaptation and may represent potential candidates for introduction into marginal areas. In addition to adaptation to different stress conditions, the ability to fix atmospheric nitrogen (N) is important in legumes and should be considered (Kebede, 2021). The percentage of nodulated plants and the number of nodules per plant are associated with N fixation in some species (Provorov and Tikhonovich, 2003). For pre-breeding purposes, the qualitative plant vigor rating, biomass, and the N measurements from non-destructive samples collected during flowering or maturity can be used (Muller et al., 2021). As the plant-associated microbes are closely linked, abiotic stresses can affect either the host plant, the *Rhizobium*, or the *Rhizobium*-legume symbioses, decreasing the N-fixing activity (Zahran, 1999). Marginal environments harbor and select diverse microbial communities, and the isolation of effective rhizobia from wild legumes for inoculating other legume crops could be an effective strategy (Ayangbenro and Babalola, 2020). Screening for tolerant N-fixing bacteria strains, as in other growth-promoting (PGP) organisms, should be considered in the selection of plant species/cultivar-specific microbial populations (Coba de la Peña and Pueyo, 2011).

Stress tolerant wild plants, such as halophytes, secretohalophytes, xerophytes and thermophytes, with a suite of desired features (food, economical or ecological) represent useful germplasm (Zhang et al., 2018), and the ecological niche models can be used to predict the adaptation in a target marginal environment (Phillips et al., 2006; Redden, 2013). Understanding the adaptive strategy simplifies crop improvement by allowing breeders to introgress new traits through traditional breeding methods or modern selection techniques (Berger et al., 2016). Likewise, knowledge of phenotypic traits in wild species would estimate the probability of adaptation *a priori*, and the global plant functional trait databases may be used as a screening tool (Kattge et al., 2011; Saatkamp et al., 2019).

THE POTENTIAL USE OF DEMOGRAPHIC MODELING FOR CROP WILD RELATIVES WITH HIGH NON-DOMESTICATION TRAITS, SUCH AS LOW-COST MANAGEMENT

Domestication could result in the loss of potentially useful "wild traits" that confer biotic and abiotic stress tolerance or specialized resource-use strategies (Van Tassel et al., 2017; Nagel et al., 2019). Pizza et al. (2021) showed that in *Clarkia pulchella*, after the eighth generation of farm cultivation, the relative fitness of the wild plants was significantly greater than the farmed plants, especially under drought stress. Genetic diversity lost over generations may be mitigated by growing out a large number of unrelated individuals (Basey et al., 2015). On the other hand, obtaining an ideal cultivar for a marginal environment can take many years of breeding resulting in abandoned programs due to low financial resources (Hajjar and Hodgkin, 2007; Muir et al., 2014; Fernie and Yan, 2019). Demographic modeling, especially in adapted pasture biotypes due to the predominance of livestock systems in marginal environments, can be used to advance their use in real production systems, until getting an advanced cultivar.

Adapted biotypes, which are not necessarily domesticated, can be very difficult to cultivate. Poor agronomic performance introduces numerous practical issues for breeders, such as difficulty in recovering a sufficient number of seeds and not being able to use standard equipment (Nutt and Loi, 1999; Nichols et al., 2012). For fodder production or restoration purposes, these traits can be used for the dispersal of desirable biotypes through demographic modeling. Dynamic population models have proven to be very useful for understanding survival and dispersal strategies of wild and semi-domesticated species. This approach is widely documented for reducing survival in weed species under different production systems (González-Andujar and Fernández-Quintanilla, 1993, 2004; Forcella et al., 2000; Colbach et al., 2005; Holst et al., 2007; Gardarin et al., 2012), as well as promoting it in legume and grass pastures (Taylor et al., 1991; Komatsuzaki, 2007; Thapa et al., 2011; Renzi et al., 2017). These models, in their simplest form, consist of five stages from seed production, seed dispersal and input into soil seed banks, through germination and seedling emergence to the reproductive phase (adult plants) (**Figure 3**). The study of these stages and processes can be the basis for identifying the causes of failure or success in the establishment and performance of the selected biotypes (Renzi et al., 2019).

The first requirement for this approach is to find the biotype(s) adapted to the target marginal environments, with acceptable forage yield and nutrition. Secondly, to reach a successful commercial scale, it is important to have seed available for farmers (Runck et al., 2020). To improve the harvestable seed yield, less seed shedding after physiological maturity, is a key objective for pre-breeding programs (Nichols et al., 2012). When the number of hectares that can be planted for cultivation I from a single hectare of seed production (S) is lower than 20 (C/S $<$ 20), models that assist natural reseeding could be a good option. This is the case of *Vicia villosa* which is well-adapted to semi-arid temperate environments, but incompletely domesticated due to extreme indeterminate growth, non-uniform maturity, large seed losses due to uneven pod dehiscence, and seed dormancy (Kissing Kucek et al., 2020a,b; Renzi et al., 2020). The demographic model was useful for expanding their adoption by farmers in marginal lands in Argentina (Renzi et al., 2017, 2019).

Several options of legumes with self-regeneration potential have been published (Carr et al., 2005; Loi et al., 2005, 2012; Norman et al., 2005; Ovalle et al., 2005; Driouech et al., 2008; Walsh et al., 2013). In a scenario of very low seed production, with a C/S ratio < 10, the natural seed dispersal should be considered in addition to the field emergence model. Under this premise, planting in patches or stripes (<<seed doses per ha) in function of the dispersal ability together with appropriate management will reduce the need for high initial seed availability. This management could be carried out in intercropping using biotypes with high resource-use complementarity (Litrico and Violle, 2015; Mazzafera et al., 2021). Thus, estimates of plant dispersal distances could be useful not only for ecological studies, but also for agronomic purposes. The dispersal traits of tall perennial pasture grasses suggest the potential applicability of this modeling approach (Thomson et al., 2011; Bullock et al., 2017). Nevertheless, complementary studies of temporal and spatial demographic dynamics are necessary.

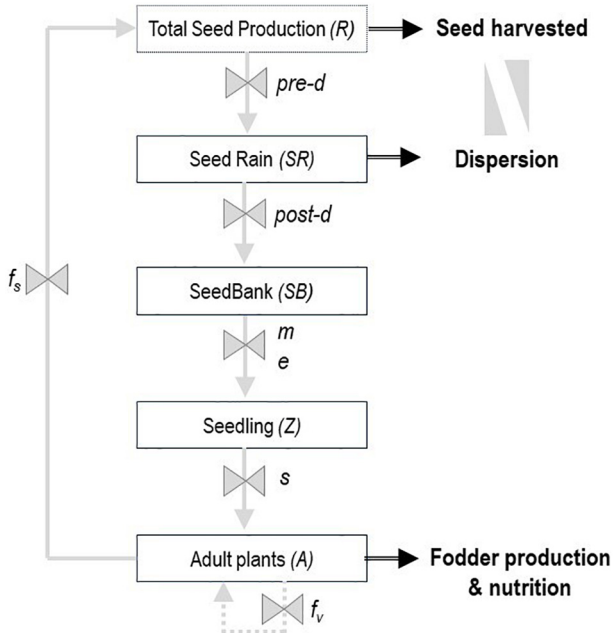


FIGURE 3 | Conceptual model of the life cycle of an annual or perennial pasture biotype. Boxes indicate state in the plant life cycle. Gray arrows indicate the processes, and black arrows the agronomic traits of interest for pre-breeding. Process variables: pre-d, predation pre-dispersal; post-d, predation post-dispersal and seed rain losses; m, mortality of seeds in the soil; e, germination and seedling emergence; s, seedlings survivorship; fs, seed fecundity; and fv, vegetative reproduction.

PRE-BREEDING TECHNIQUES FOR TRANSFERRING USEFUL TRAITS TO THE CROP

Crop wild relatives are an untapped source of genetic diversity and a critical resource to meet food security needs and the challenges of new production systems, especially in response to climate change (Zhang et al., 2017; Bohra et al., 2021). However, three major factors discourage the use of CWRs in plant breeding (Zamir, 2001): (1) poor agronomic performance of CWRs, mostly due to the presence of undesirable traits such as shattering and seed dormancy; (2) crossing barriers between crops and their wild relatives, which limits the production of fertile offspring; and (3) the transfer of undesirable traits physically linked to the target trait, known as linkage drag (Zamir, 2001; Hajjar and Hodgkin, 2007; Shelef et al., 2017; Fernie and Yan, 2019). Therefore, to facilitate the use of CWRs in breeding programs, it is necessary to focus on the development of systematic strategies for the characterization and use of CWRs. Pre-breeding here refers to all activities designed to identify and transfer desirable traits or alleles from genetic materials that cannot be used directly in plant breeding (Prohens et al., 2017; Tefera, 2021). Pre-breeding produces intermediate genetic materials that can be used for breeders to produce elite cultivars. This section provides a review of distinct pre-breeding strategies to facilitate the use of CWRs in breeding programs, focused on the utilization of CWR for improving the tolerance to stressful conditions associated to marginal agricultural lands.

In the broad sense, strategies to incorporate CWR into breeding programs can be classified as **"choose first"** or **"cross first"** (Dempewolf et al., 2017). In "choose first" wild accessions are chosen from a larger number of accessions, based on phenotypic, genotypic, or eco-geographic merits. Chosen accessions are expected to carry a desirable trait, then they are used in a target crossing design. In "cross first" one or more wild accessions are crossed with elite cultivars, and then the progeny is evaluated, this approach is useful when the trait of interest cannot be directly measured in the wild donor.

Choose First Strategy: Target Hybridization

Target hybridization is the classic example of the "choose first" strategy. Generally, a single wild accession carrying a single trait of interest (e.g., herbicide resistance, disease resistance) is used as donor and one elite cultivar, with good agronomic performance but lacking the trait of interest, is used as recurrent parent (Breseghello and Coelho, 2013). Crossing and backcrossing with positive selection for the target trait are used to incorporate the target trait and to recover most of the recurrent parent genome. This approach is routinely used in breeding programs to improve tolerance to pests and diseases (Hajjar and Hodgkin, 2007; Larkan et al., 2013; Seiler et al., 2017; Bohra et al., 2021). Using this approach, molecular markers can be used to map the region underlying the trait of interest, and to accelerate the recovery of the elite genome through assisted backcrossing (Breseghello and Coelho, 2013). The first step of target hybridization is to identify the suitable wild accession carrying the trait of interest (Zamir, 2001; Bahrami et al., 2021). As mentioned above, wild accessions can be selected based on phenotypic, genotypic, or eco-geographic merits. For

phenotypic selection, several wild accessions are directly screened for the trait of interest along with elite cultivars; accessions outperforming elite cultivars for the target trait are selected for the next stage (Bahrami et al., 2021). Phenotypic screening has been used to identify wild accessions with increased tolerance to several stressful conditions associated to marginal agricultural lands, such as salinity in wild tomato (Pailles et al., 2020), freezing in wild sunflower (Hernández et al., 2020), drought in wheat and barley (Nevo and Chen, 2010), heat in wild rice (Scafaro et al., 2016; Bheemanahalli et al., 2017), wild sunflower (Hernández et al., 2018, 2020), and wild barley (Bahrami et al., 2021). Genotypic information can also be used to identify valuable wild accessions. For example, Buitrago-Bitar et al. (2021) identified wild accessions of tepary bean carrying novel alleles for previously identified drought-responsive genes. With the increasing amount of reported candidate genes for abiotic stress tolerance, genes-specific hybridization probes can be designed to target multiple candidate genes at once in many samples before next generation sequencing (Weitemier et al., 2014), thus accelerating the discovery of novel alleles of relevant genes. Lastly, eco-geographic tools can be used to identify possible sources of abiotic stress tolerance (e.g., Khazaei et al., 2013; Kantar et al., 2015; Stenberg and Ortiz, 2021). Eco-geographic approaches gather environmental variables from collection sites such as temperature, precipitation, and soil characteristics. This approach assumes that wild accessions from sites prone to a given abiotic stress (e.g., drought, cold or heat) likely carry adaptive alleles to cope with these environmental challenges (Kantar et al., 2015; Anderson et al., 2016). Phenotypic, genotypic, and eco-geographic approaches can be combined. Landscape genomics is a powerful approach that combines eco-geographic and genomic data to identify loci underlying environmental adaptation (Joost et al., 2007). This approach does not require phenotypic experiments, thus allowing the evaluation *in silico* of hundreds to thousands of accessions. Several climatic databased, including WorldClim (Fick and Hijmans, 2017), Envirem (Title and Bemmels, 2018), and SoilTemp (Lembrechts et al., 2021), along with genomic information can be used to link geographic coordinates of any accession with local environmental conditions and genomic data, increasing the value of *ex situ* collections. Recent examples focused on wild relatives of soybean (Anderson et al., 2016), wheat (Brunazzi et al., 2018), narrow-leafed lupin (Mousavi-Derazmahalleh et al., 2018), and chickpea (von Wettberg et al., 2018). Once the suitable accession is identified, a crossing and backcrossing design with an elite cultivar is initiated. As this approach uses only one wild accession as donor, genome-wide increases of genetic diversity are not expected. The advantage of this approach is the efficient transfer of traits regulated by a few genes, such as disease resistance (Seiler et al., 2017), and it is well-known by breeders. However, it is time-consuming and its success in traits with complex genetic architecture is not guaranteed.

Cross First Strategy: Wide Hybridization

The cross first strategy consists of developing populations of lines with introgressions from CWR into the genetic background of crops, aiming to generate elite materials carrying genome fragments from CWR (Tanksley and McCouch, 1997; Dempewolf et al., 2017; Prohens et al., 2017). Such populations can be used to identify genomic regions underlying adaptive traits, but they can also be directly incorporated into breeding programs (von Wettberg et al., 2018; El Haddad et al., 2021). There are many ways for developing populations with introgression from CWR; Chromosome Segment Substitution Lines (CSSL), Nested Association Mapping (NAM) populations, and Multiparent Advanced Generation Intercross (MAGIC) populations. These populations are often developed in an unfocused manner regarding target traits, i.e., the aim is to generate populations with as high genetic diversity from CWR as possible, thus populations are useful to map most agronomic traits in many environments. However, multi parent populations can be developed in a focused manner, selecting parents with particular features, such as tolerance to biotic or abiotic stress (reviewed in Prohens et al., 2017; Scott et al., 2020).

Chromosome Segment Substitution Lines

Chromosome Segment Substitution Lines were designed and used for mapping QTL in many crops (Balakrishnan et al., 2019). CSSL form a population of lines with chromosomal segments from one wild accession into an elite background (Balakrishnan et al., 2019). Ideally, each CSSL harbors a single segment of the donor and the whole donor genome is distributed segment-wise in the entire population of CSSL. In pre-breeding, CSSL has been used in several crops, such as rice, wheat, barley, maize, and soybean to identify and transfer alleles from wild species, including alleles associated to drought, heat, and freezing stress (reviewed in Balakrishnan et al., 2019). By definition, with this approach a single wild accession is used as donor and a single elite cultivar as recurrent parent, although CSSL populations using the same recurrent parent and distinct wild donors can be combined (Singh et al., 2020).

Multiparent Populations

In the last decades, multiparent populations of crop species were developed and largely used to explore the genetic architecture of agronomic traits (Scott et al., 2020). Nested Association Mapping (NAM) and Multiparent Advanced Generation Intercross (MAGIC) populations are the most popular designs. They were designed to improve the resolution of QTL analysis with biparental populations and to reduce the confounding effects of population structure of association mapping (Gage et al., 2020). While NAM populations can be seen as a collection of biparental populations with a common parent (e.g., Yu et al., 2008; Hu et al., 2018), MAGIC populations have more complex crossing designs, commonly involving 4, 8, or 16 parents (Zamir, 2001; Gage et al., 2020; Scott et al., 2020). Such differences in the crossing designs determine that lines from NAM and MAGIC populations differ in their genetic composition, even when the same parents are used. In the NAM populations,

lines are grouped into families, with as many families as donor parents, thus the genomes of NAM lines are a mosaic of only two parents, and haplotype diversity is constrained by the common parent (Zamir, 2001; Gage et al., 2020). On the contrary, the genomes of MAGIC lines are a mosaic of all founders, and haplotype diversity grows with the number of founders, although it is constrained by the number of lines in the population (Zamir, 2001; Scott et al., 2020). More than 50 multiparent populations were developed for several crop species (reviewed in Scott et al., 2020), however, only four of them included CWR as founders, three for barley and one for maize (Scott et al., 2020). In multiparent populations, the selection of founders is the most critical step, as it determines the pool of genetic variation segregating in the population. Choosing founders as genetically diverse as possible maximizes the population's utility for mapping agronomic traits in multiple environments (Gage et al., 2020; Scott et al., 2020). However, for pre-breeding, a more conservative selection of founders will produce populations with higher overall agronomic performance, and therefore more attractive for breeders. In the case of NAM populations, after crossing the elite cultivar with CWR, one or more cycles of backcrosses can be implemented before selfing to improve the overall agronomic performance of the population (Chen et al., 2019). In the case of MAGIC populations, a trade-off between the overall agronomic performance and the novel genetic variation is expected, i.e., the larger the proportion of elite cultivars as founders the larger the overall agronomic performance and the lower the novel genetic variation, and vice versa.

Genomic Selection and Multiparent Populations

The complex genetics controlling most abiotic stress tolerances presents a challenge for crop breeders to incorporate many CWR alleles into their breeding programs. Genomic selection (GS) is an efficient approach that was pioneered in animal breeding, where complex, polygenic traits are the norm (Goddard and Hayes, 2007). Genomic selection has been refined for plant breeding and adopted as a core methodology by many breeding programs (Crossa et al., 2017). This approach could be used to accumulate increasing numbers of alleles associated with stress tolerance and shift the breeding populations from stress-sensitive to stress-tolerant over many generations.

Genomic selection is increasingly common for a range of crops, e.g., barley (Gonzalez et al., 2021), pea (Al Bari et al., 2021), chickpea (Varshney et al., 2021), wheat (Muleta et al., 2017), and sorghum (Yu et al., 2016). However, GS to select within CWR collections has been proposed, but examples have yet to be published (Bohra et al., 2021). With the genotyping of larger CWR collections (e.g., Song et al., 2015; Sansaloni et al., 2020), it is expected this approach may be used in the future as it has been proven effective in plant breeding programs (Merrick and Carter, 2021). The importance of GS may increase for CWR pre-breeding programs as it allows for efficient introgression of beneficial alleles for polygenic traits with reduced linkage drag (Wang et al., 2017). Genetic selection has the advantage of selecting superior progeny based on genotypes alone using phenotyped training populations (Meuwissen et al., 2001). The first demonstration of GS in pre-breeding was in exotic maize populations successfully selecting for yield (Combs and Bernardo, 2013). Genomic selection in CWR pre-breeding was also validated recently in soybean (Beche et al., 2021). Very good prediction accuracies for several quantitative traits were reported using a NAM breeding population with three wild Plant Inventory parents (Beche et al., 2021). An excellent example for pre-breeding for marginal lands using focused identification of germplasm strategy (FIGS) is found in studies with barley, wheat and faba bean landraces (Endresen et al., 2011; Khazaei et al., 2013). FIGS is another machine learning application that takes multivariate data sets of *a priori* knowledge (phenotypes, environmental) to identify the potential most useful accessions (Bari et al., 2012). Stenberg and Ortiz (2021) suggest improving the FIGS model of adaptive processes (natural selection) by adding non-adaptive processes (gene flow and genetic drift) to hit the most intensive evolutionary hotspots to capture elusive traits followed by genomic selection.

In summary, the "choose first" strategy is more suitable for incorporating traits regulated by one or a few major loci (e.g., herbicide or disease resistance alleles) while the "cross first" is more suitable for polygenic traits, which is expected for most traits associated to adaptation to marginal agricultural lands. Multiple parent populations, especially MAGIC, are well-suited for the cross first strategy. Such populations are useful to discover agronomically relevant loci, to improve genetic diversity of pre-bred populations, and to directly incorporate them to breeding schemes. However, we identified a lack of multiparent populations (MPPs) that include CWR as founders, meaning that current MPPs are exploiting only a small fraction of species' genetic diversity. Therefore, we call for a systematic development of MAGIC populations, which should include CWR, elite cultivars, and landraces as founders. The outlined advantages of MAGIC populations for both basic science and plant breeding should facilitate the creation of public-private pre-breeding partnership programs aiming to develop cultivars well-adapted to marginal agricultural lands. Although universal MAGIC populations can be used to discover agronomically relevant loci by multiple research groups, we encourage (when possible) the development of MAGIC populations with local founders to exploit local adaptation.

DE NOVO DOMESTICATION AND GENOME EDITING

Since domestication began approximately 12,000 years ago, some significant events determined a deep change in the evolution of crops and their wild relatives. Fernie and Yan (2019) divided the history of crop improvement into four breeding generations, the first generation with breeding based on phenotype selection; the second generation with hybrid breeding and green revolution with dwarf plants and higher yields; a third generation called

or "biotechnology-based breeding" with the arrival of genetically modified crops. Currently, the fourth generation of breeding is running, with genome editing and precision breeding. In fact, the fourth-generation breeding is determined by new plant breeding techniques like *cis*-genesis (Jacobsen and Schouten, 2007) and genome editing (Zsögön et al., 2017), mainly CRISPR/Cas (Sukegawa et al., 2021). *Cis*-genesis consists of the genetic transformation of a crop with CWR's genes, without the introduction of reporters or selectable markers from other organisms, avoiding linkage drag. This is particularly interesting in the case of the secondary and tertiary genepool species (Harlan and de Wet, 1971) with strong hybridization barriers.

Genome editing techniques involve zinc-finger nucleases (ZFNs), transcription activator-like effector nucleases (TALENs), and clustered regularly interspaced short palindrome repeats associated protein 9 (Cas9), CRISPR/Cas systems (Manghwar et al., 2019; Sedeek et al., 2019; Van Tassel et al., 2020; Molla et al., 2021). ZFNs and TALENs are protein-based and require protein engineering for every user-defined sequence. Instead, CRISPR/Cas is a RNA-guided system that induces double-stranded DNA breaks by the action of Cas9 nuclease at a genome corresponding location (Belhaj et al., 2013; Altpeter et al., 2016; Rodríguez-Leal et al., 2017). Among genome editing techniques in plants, CRISPR/Cas9 has become the most popular (Altpeter et al., 2016; Pacher and Puchta, 2017; Das et al., 2019). The CRISPR/Cas9 system can generate stable and heritable mutations in genes that cannot be distinguished from a natural mutation at the same locus, without affecting the existing valuable traits (Belhaj et al., 2013; Arora and Narula, 2017). Since the main domestication genes in most of the major crops have been studied (see reviews by Kantar et al., 2017; Purugganan, 2019), the new gene editing tools would allow neo-domestication avoiding the linkage drag. *De novo* domestication or neo-domestication is defined as the targeted introduction of domestication genes into non-domesticated plants, this represents an important opportunity for fitting cultivated species to the climatic niche where they live (Fernie and Yan, 2019). In addition, genome editing allows to incorporate new adaptation attributes present in wild materials into cultivated ones, bringing resilience under the unfavorable conditions of climate change (Van Tassel et al., 2020). This is possible since the whole genome sequences for many crops and their wild species are now available (Bohra et al., 2021; Ramsay et al., 2021). However, it should be emphasized that this approach has yet to be fully tested and is unlikely to transfer all the beneficial traits accumulated in crops over centuries of generations, such as complex traits like grain yield, which is controlled by many genes.

Genome editing (GE) can be used for several purposes like to activate or suspend the function of any gene. Ghoshal et al. (2021) showed that with epigenome engineering it is possible to achieve heritable methylation, gene silencing, and delayed flowering time phenotypes. Hence, stable heritable epigenetic modifications in flowering time would allow researchers and breeders to overcome the crossing barriers of the secondary and tertiary genepool, facilitating crossings of CWRs with related crops (Cable et al., 2021). Genome editing can also be used to knock out genes. For example, increasing grain number and larger grain size in rice was possible by knocking out three mutations on negative regulators of yield (Mishra et al., 2018). In addition, knocking out the self-incompatibility gene S-Rnase allowed re-domestication of potato into an inbred-line based diploid crop for genetic improvement (Ye et al., 2018). This demonstrated the utility of this approach in four different Solanum tuberosum clones, opening possibilities in both future diploid breeding and basic research in self-incompatible crops.

Another application for GE is to generate novel alleles of any gene. For breeding drought tolerance in maize, novel allelic variation for ARGOS8 locus was generated by changing the DNA sequence at the native ARGOS8 (Shi et al., 2017). Genome editing could also add genes that do not exist in an original genome. There is also work on CRISPR/Cas9-mediated HDR (homology-directed repair) for editing genes that confer herbicide resistance, and to transfer an allele from a wild rice variant into a cultivated variant to increase yield potential. In addition, GE makes it possible to delete any sequence including large chromosomal fragments or even the entire chromosome (Xiao et al., 2013). This could be an advantage for the secondary and tertiary genepool species (Harlan and de Wet, 1971). Introgression of beneficial alleles from CWR into the cultivated gene pool has been a challenge when reproductive barriers are present. For instance, the genus *Helianthus*, native to North America, comprises 52 species including cultivated sunflower, *H. annuus* L. which has emerged as a model for genetic studies of adaptation, hybridization, and speciation. In particular, *H. annuus* and *H. petiolaris* are chromosomally divergent species, differing by a minimum of seven translocations and three inversions (Rieseberg et al., 1995). Notably, the first source of cytoplasmic male sterility for hybrid varieties' development was discovered in *H. petiolaris* (Leclercq, 1969) and all currently grown sunflower hybrids are developed on cytoplasmic male sterility *petiolaris* type mothers. Chromosomal rearrangements are common in CWRs and drastically decrease recombination in crosses with crops by preventing the normal pairing of homologous chromosomes. The CRISPR/Cas system could be used to alter the frequency and guide homologous recombination to overcome these structural barriers between related species, thus opening new avenues to genomic restructuring and chromosomal engineering (Fauser et al., 2014).

The tertiary gene pool can also benefit from GE. Toda et al. (2019) demonstrated the possibility of genome editing in rice and maize zygotes, opening an avenue to gene manipulation in CWR wide crosses aiming to incorporate valuable traits to crops.

PRE-BREEDING RESOURCES AND DATA REPOSITORY

Utilizing CWR in breeding and crop improvement requires that researchers have access to germplasm resources. International agreements, particularly the Nagoya Protocol to the Convention on Biological Diversity and the International Treaty on Plant Genetic Resources for Food and Agriculture, the two international agreements that govern the collection and sharing of crop genetic resources, enshrine access and benefit sharing

as core principles, so that those who give germplasm resources benefit from them too. Since much CWR diversity comes from less developed regions of the world, yet has historically primarily been harnessed in the less diverse global north, there are real historical inequalities that access and benefit sharing (ABS) frameworks should address. Negotiations around ABS in treaties have increasingly focused on Digital Sequence Information (DSI) associated with CWR (Rohden and Scholz, 2022; von Wettberg and Khoury, 2022). Digital Sequence Information may encompass not only DNA sequence data associated with germplasm accessions, but also CWR passport data, traditional ecological knowledge on the preparation or use of varieties (Brink and van Hintum, 2022). This information, as our discussion above shows, can be incredibly powerful as a breeding tool, yet is very unequally distributed globally.

For those seeking germplasm access, there are a number of data sources for CWR as well as other databases with additional data and access for ordering seed or propagule samples. The Global Biodiversity Information Facility (GBIF) repository remains an essential database and data repository for discovery of species locations that includes most herbaria globally[1] (Lane and Edwards, 2007). Efforts by the Global Crop Diversity Trust have greatly improved knowledge of target CWR taxa through their Genesys database[2] (Dempewolf et al., 2014) and one of their partners with GRIN-Global[3] (Postman et al., 2010). A number of CWR characterization, evaluation and genotype data sets can be found here under the Genesys 'Dataset' repository. Genesys and GRIN-Global are data repositories only; no user analysis tools are present or planned in this resource.

As noted by Brink and van Hintum (2022), most genebanks do not plan to host genotype data resources. However, the GRIN-Global development team now has modules to improve the storage and downloading of crop genetic resource genotype data sets (see footnote 3). Although sequence resources for CWRs are increasing, currently most plant genetic resource sequencing datasets are on domesticated material, notable examples are found for several crops (Song et al., 2015; Sansaloni et al., 2020; Hellwig et al., 2021). A very promising development is the expansion of the Germinate database to handle pre-breeding populations from CWRs (Raubach et al., 2021). The Germinate software will provide the CWR pre-breeding community critical tools for working with and selection/advancement of introgression lines for growing in marginal production areas. Adoption of FAIR data standards will increase the availability of CWR evaluation data for pre-breeding efforts (Wilkinson et al., 2016).

IN SITU CONSERVATION

For those harnessing CWRs, *ex situ* collections are critical as access points. But *ex situ* conservation alone is unable to fully conserve crop diversity, particularly for CWR that have historically been smaller parts of germplasm collections and harbor orders of magnitude more genetic diversity than domesticated accessions (Khoury et al., 2022). *In situ* conservation efforts for CWR have been growing over the last decade (Phillips et al., 2019) and can be essential to access traits of interest that are not covered by *ex situ* collections. *In situ* genetic reserve conservation may be defined as "the location, designation, management and monitoring of genetic diversity in natural wild populations within defined areas designated for active, long-term conservation" (Maxted et al., 1997). Some of the success in these efforts has been to harness existing conservation areas, often established for large animal preservation but also protecting CWR inadvertently. Dedicated efforts at *in situ* conservation have lagged, particularly in Vavilovian centers of origin where CWR taxa are most diverse and abundant. Protecting CWRs in their natural habitats is an essential strategy to prevent extinctions, especially where *ex situ* conservation of sufficient genetic diversity is practically or economically unfeasible (León-Lobos et al., 2012). There is a preference for *in situ* conservation, because it has the advantage of maintaining the dynamic evolution of the CWR diversity itself in relation to parallel biotic and abiotic changes. In the span of only three decades, for example, there was a shift in allelic diversity related to flowering time genes in wild barley (Qian et al., 2020) likely as response to global warming, and even an overwhelming local adaptation and ecological differentiation. Gap Analysis (e.g., Maxted et al., 2008) has been applied for hundreds of CWRs to find areas where *ex situ* collections and *in situ* conservation areas fail to protect the full range of diversity in CWR (Vincent et al., 2019; Khoury et al., 2020; Zair et al., 2021).

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[2] www.genesys-pgr.org

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APPENDIX 5

Click beetle larvae from Cretaceous Burmese amber represent an ancient Gondwanan lineage

Kundrata, R., Rosa, S. P., Triskova, K., Packova, G., Hoffmannova, J., & Brus, J. (2025). Click beetle larvae from Cretaceous Burmese amber represent an ancient Gondwanan lineage. *Scientific Reports*, 15(1). https://doi.org/10.1038/s41598-024-80950-w

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Click beetle larvae from Cretaceous Burmese amber represent an ancient Gondwanan lineage

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The click beetles (Elateridae) represent the major and well-known group of the polyphagan superfamily Elateroidea. Despite a relatively rich fossil record of Mesozoic Elateridae, only a few species are described from the Upper Cretaceous Burmese amber. Although Elateridae spend most of their lives as larvae, our knowledge on immature stages of this family is limited, which is especially valid for the fossils. So far, only a single larval click beetle has been reported from Burmese amber. Here, we describe two larval specimens from the same deposit which based on their morphology unambiguously belong to the predominantly Southern Hemisphere subfamily Pityobiinae, being the most similar to the representatives of tribe Tibionemini. However, since the larvae of the closely related bioluminescent Campyloxenini have not yet been described, we place our specimens to Tibionemini only tentatively. One species of Pityobiinae was recently described from Burmese amber based on adults, and we discuss if it can be congeneric with the here-reported larvae. Recent representatives of the Tibionemini + Campyloxenini clade are known from South America and New Zealand, and this group is hypothesized to have a Gondwanan origin. Hence, the newly discovered Burmese amber larvae may further contribute to a recently highly debated hypothesis that biota of the resin-producing forest on the Burma Terrane, which was probably an island drifting northward at the time of amber deposition, had at least partly Gondwanan affinities. The discovery of enigmatic click beetle larvae in the Upper Cretaceous Burmese amber sheds further light on the palaeodiversity and distribution of the relatively species-poor Gondwanan clade of click beetles, which contain a recent bioluminescent lineage, as well as on the taxonomic composition of the extinct Mesozoic ecosystem.

Keywords Australia, Elateridae, Distribution, Fossil, Morphology, Pityobiinae

The Upper Cretaceous amber of northern Myanmar, also known as Burmese amber, Burmite, or Kachin amber, is recently one of the best explored fossilized resins in the World. After its re-discovery in the beginning of the 21st century[1], it has become to be one of the most important sources of our knowledge on the Cretaceous biota. The known palaeodiversity of organisms trapped in Burmese amber has increased dramatically over the past few years. In 2019, Ross[2] published the complete list of taxa preserved in Burmese amber, which has been updated annually since then[3–7]. Since 2019, the total known number of species has more than doubled. Up to the end of 2023, about 2,800 species have been described or recorded from Cretaceous amber of Myanmar[8].

The Burmese amber is sourced from the Hukawng Valley in the Myitkyina District of Kachin State in northern Myanmar. The U–Pb dating of zircon crystals of volcanic clasts within the amber bearing horizons has given a maximum age of 98.79 ± 0.62 Ma, making the deposit Upper Cretaceous (lower Cenomanian) in age[9]. It is distinct and differs in age from the Tilin amber (~ 72.1 Ma)[10] found in central Myanmar. Relatively recently, also the Hkamti site (109.7 ± 0.4 Ma)[11] located southwest of the Hukawng Basin started producing amber. Burmese amber is thought to have been produced by trees belonging to either the Araucariaceae or Cupressaceae/Sciadopityaceae[1,12,13]. The organisms trapped in Burmese amber suggest a warm, tropical ecosystem[14]. The inclusions of not only terrestrial but also of aquatic species suggest that the resin-producing forests were located near estuarine or freshwater habitats[15–17].

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The amber deposit lies on the Burma Terrane, or West Burma Block, a former Gondwanan landmass presently situated in Myanmar which has a debated tectonic history[18–20]. The Burma Terrane broke off from northeastern Australia and drifted northward; however, the timings of when it broke off and when it accreted to the southern margin of Asia and became to be a part of Southeast Asia are unclear as various studies produce contradictory results[20–24]. Westerweel et al.[22] proposed that the Burma Terrane was part of a Trans-Tethyan island arc and stood at a near-equatorial southern latitude at ~95 Ma which suggests an island endemism for the organisms trapped in Burmese amber[25]. Nevertheless, there is an ongoing debate if the Upper Cretaceous biota trapped in Burmese amber has more affinities to Gondwana or Laurasia[21,23,26–29].

The click beetles (Elateridae) represent the major group in the polyphagan superfamily Elateroidea. More than 11,000 described extant and extinct species from all zoogeographic realms are currently classified in 18 subfamilies[30,31]. This group is famous for both scientists and non-scientists due to the presence of a clicking mechanism in vast majority of its species[32,33] and because it contains important economic pests[34], bioluminescent groups[35,36], and several morphologically modified paedomorphic lineages[37,38]. It is, therefore, rather surprising, that the monophyly, classification and phylogenetic relationships of Elateridae are still a matter of debates[30,31,39–42]. The immature stages are insufficiently researched in Elateridae; however, the known information suggests that the larval morphology may provide an important source of data for phylogenetic reconstructions as well as for defining higher taxa[35,43–46]. For example, the differences in larval morphology are the most reliable characters to separate two large and well-known subfamilies Elaterinae and Dendrometrinae[35,47].

Fossil Elateridae are represented by more than 250 described species, of which more than half are Mesozoic[48]. Although several click beetle species were described from Triassic, their systematic placement is largely unclear[48,49]. However, the Triassic origin of the group cannot be ruled out since the Jurassic click beetle fauna already consisted of more than 100 described species[48,50]. Although the click beetle fauna is well represented in Burmese amber, only several species have been formally described to date, all from adult males[51]. So far, only one click beetle larva has been reported from Burmese amber[52].

In this study, we report two larval specimens from the Upper Cretaceous amber of northern Myanmar which based on their morphology belong to the mostly Southern Hemisphere click beetle subfamily Pityobiinae[31,39,53].

Systematic palaeontology

Order Coleoptera Linnaeus, 1758.
Suborder Polyphaga Emery, 1886.
Superfamily Elateroidea Leach, 1815.
Family Elateridae Leach, 1815.
Subfamily Pityobiinae Hyslop, 1917.
Tribe Tibionemini Motyka et al., 2023.

Remarks. The here-examined larvae are placed in Pityobiinae based on the following combination of characters: dorsoventrally flattened body, more depressed on head and prothorax, the cuticle of head and prothorax more sclerotized than that of abdomen, the ventral surface of abdomen less sclerotized than the dorsal surface, the head subparallel-sided, the mandible with retinaculum, the labium with postmentum triangular, the apices of maxillary stipites approximate, antennal sensorium dome-shaped, the segment IX with a notch at apex and a pair of urogomphi, and anal hooks absent[53,54]. Within Pityobiinae, we place the larvae tentatively in Tibionemini based on the following combination of characters: adnasalia approximate and longer than nasale, the absence of a transverse carina as well as a median longitudinal suture on sternum IX, and the lateral region of tergum IX as sclerotized and heavily pigmented as a dorsal region (Fig. 2F)[53,55]. The only genus of Pityobiinae known from Burmese amber is *Cretopityobius* Otto. However, *Cretopityobius* is more similar to *Pityobius* LeConte (Pityobiini) than to *Tibionema* Solier (Tibionemini). Hence, the generic placement of the here-reported fossil larvae remains unclear. For more details see Discussion.

Unidentified genus (larval stage)

Figures 1, 2, 3, 4 and 5.

Material examined

Two larval specimens deposited in NMPC: NM-T3536 (BUR0112) and NM-T3537 (BUR0113). The specimen NM-T3536 is included in a transparent, pale yellow amber piece with dimensions of about 20.5 × 14.5 × 4.0 mm, with several syninclusions (debris and remains of an unidentified insect). The specimen NM-T3537 is included in a transparent, dark yellow amber piece with dimensions of about 20.0 × 15.2 × 4.0 mm, with numerous syninclusions (debris and an unidentified small arachnid).

Type horizon and locality

Upper Cretaceous, lower Cenomanian (98.79 ± 0.62 Ma), based on U–Pb dating of zircons by Shi et al.[9]; from amber mine in Hukawng Valley, Tanai Township, Myitkyina District, Kachin State, northern Myanmar.

Diagnosis

The here-examined fossil larvae can be easily recognized based on the following combination of characters. Body dorsoventrally flattened, head and prothorax apparently more sclerotized than metathorax and abdomen, intersegmental membranes visible, vestiture consisting of fine long setae, without asperite-like setae. Head flat, nasale produced, wider than long, tridentate, adnasalia approximate, frons lyre-shaped with posterior part abruptly narrowed and tapered at apical 2/3, dorsal epicranial ridges absent, epicranial stem short, coronal



Fig. 1. Habitus of click beetle larvae from Burmese amber. (**A**–**B**) Larval specimen NM-T3536; dorsal and ventral view, respectively. (**C**–**D**) Larval specimen NM-T3537; dorsal and ventral view, respectively. Scale bars: 2 mm.

suture absent, postmentum triangular, stipites contiguous at base, mandible unidentate, with small retinaculum mesally. Mesonotum, metanotum and abdominal mediotergites I–VIII with L-shaped pigmented impressions near anterior corners; legs with spine-like setae. Abdominal segment IX with long bifurcated urogomphi and spine-like setose tubercles; transverse carina of sternum IX and anal hooks absent. For comparison with related groups see Table 1 and Discussion.

Description

Body about 9.5 mm long and about 1.6 mm wide at the widest place in specimen NM-T3536 (Fig. 1A,B), about 9.0 mm long and about 1.1 mm wide at the widest place in specimen NM-T3537 (Fig. 1C,D), dorsoventrally flattened. Tegument of head and prothorax evenly darkly sclerotized, brown, dorsal surface of mesothorax, metathorax and abdominal segments I–VIII partly or entirely lighter than prothorax; articulating area between segments and median exuvial line membranous; ventral surface of abdominal segments I–VIII and segment X lighter than dorsal surface; anterolateral region of mesonotum, metanotum and abdominal mediotergites I–VIII with prominent pigmented L-shaped impression extending from lateral part mesally in about 90-degree angle (Fig. 5F,H,J); claws and spine-like setae on legs darker. Vestiture consisting of sparse long and short brownish setae; asperities absent.

Head (Figs. 2A,B and 4A,B and 5A,B,I) excluding mouthparts 1.2–1.3 times wider than long, sides parallel, prognathous, sclerotized, flattened, shortly retractable into prothorax; dorsal surface flat, moderately densely punctate, punctures large, each side with one lateral long seta at antennifer base, one dorsolateral long seta posterior to antennifer (at anterior third), one long seta dorsally and one long seta laterally between mid and posterior third, one large puncture dorsally near posterior margin; dorsal epicranial ridges and stemmata absent; epicranial stem very short, coronal suture and endocarina absent.

Frontal arms lyre-shaped, frons with anterior corners rounded, one long seta at base of adnasalia and sparse punctures mainly distributed on margins; posterior part of frons abruptly narrowed and tapered at apical 2/3. Nasale (Figs. 2A, 4A,B, and 5A,I) produced, about 3 times wider than long, tridentate, median tooth longer than lateral teeth, few fine setae at base between lateral and median teeth; adnasalia twice longer than nasale,

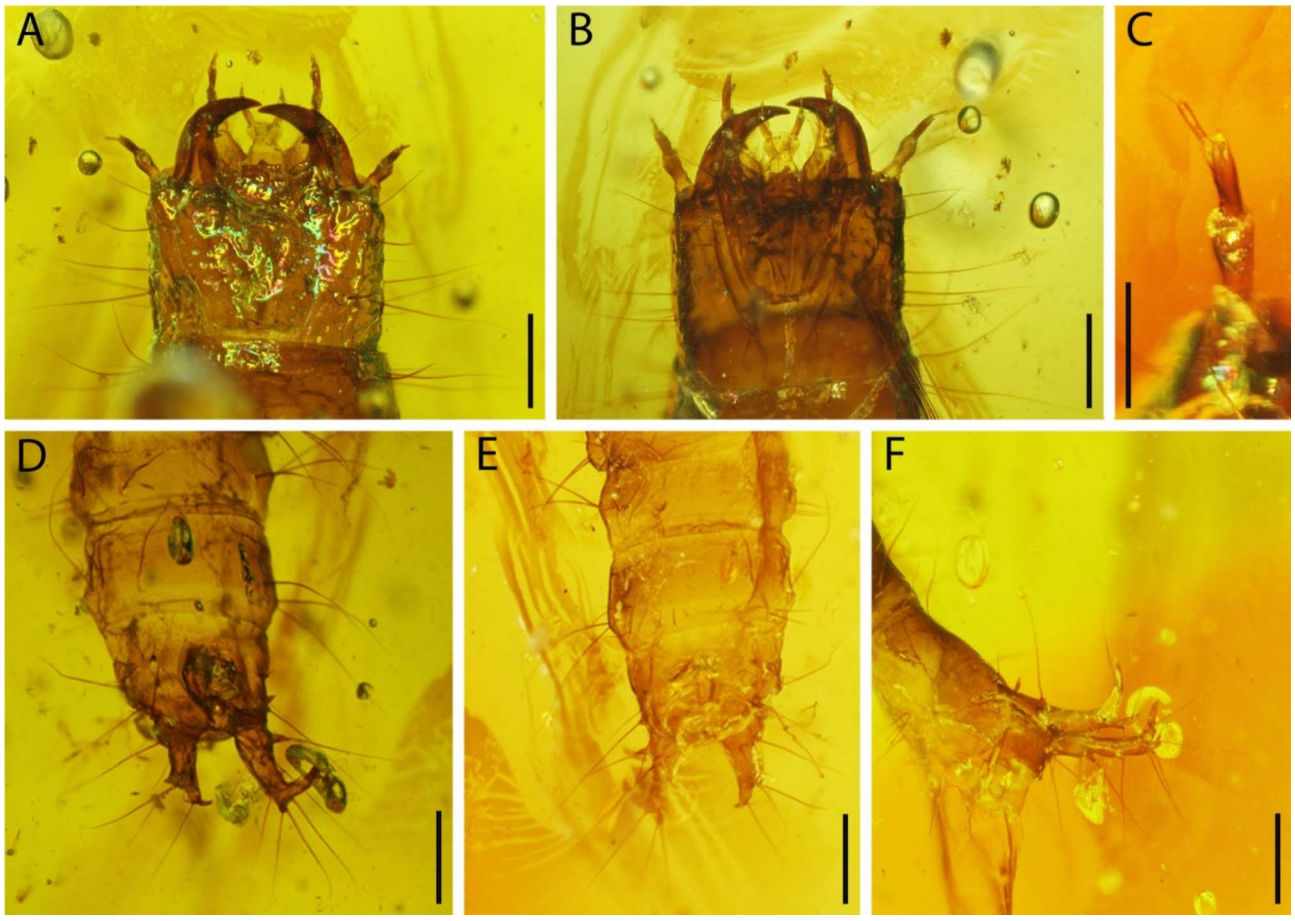


Fig. 2. Body parts of click beetle larva from Burmese amber (specimen NM-T3536). (**A**) Head; dorsal view. (**B**) Head; ventral view. (**C**) Left antenna; dorsal view. (**D**) Abdominal apex; dorsal view. (**E**) Abdominal apex; ventral view. (**F**) Abdominal apex; lateral view. Scale bars: (**A**, **B**, **D**–**F**) 0.50 mm, (**C**) 0.25 mm.

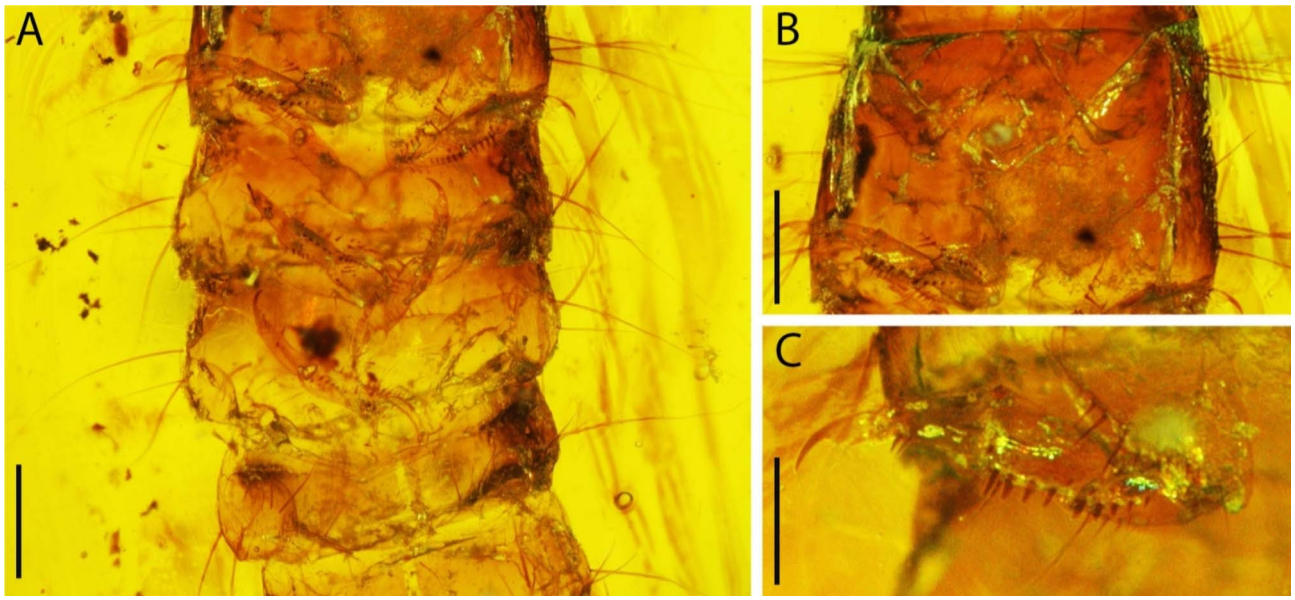


Fig. 3. Body parts of clickbeetle larva from Burmese amber (specimen NM-T3536). (**A**) Thorax with legs; ventral view. (**B**) Prothorax; ventral view. (C) Right proleg; ventral view. Scale bars: (**A**, **B**) 0.50 mm, (**C**) 0.25 mm.

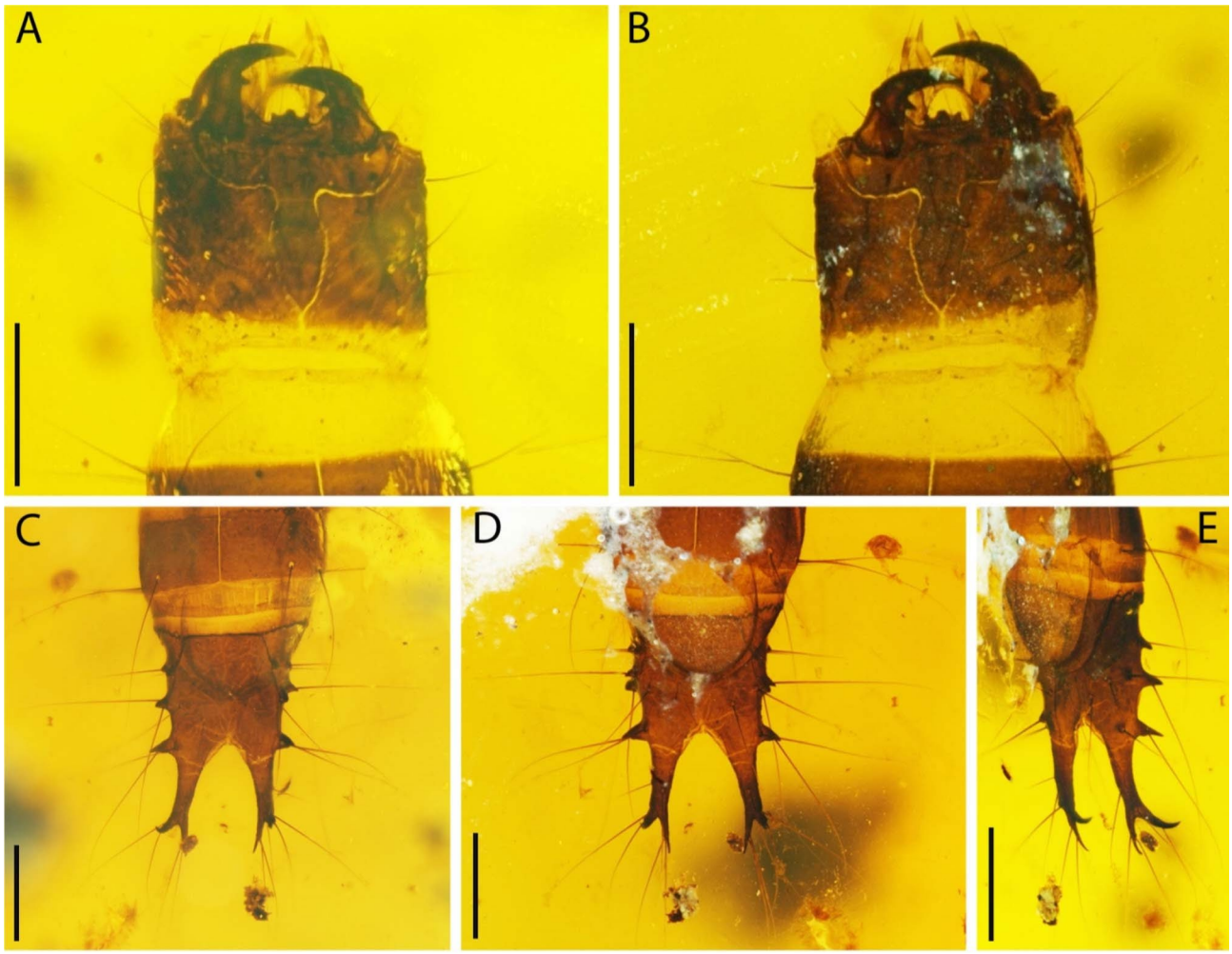


Fig. 4. Body parts of click beetle larva from Burmese amber (specimen NM-T3537). (**A**) Head; dorsal view. (**B**) Head; ventral view. (**C**) Abdominal apex; dorsal view. (**D**) Abdominal apex; ventral view. (**E**) Abdominal apex; lateral view. Scale bars: 0.5 mm.

approximate, separated by distance 0.6–0.7 times as wide as width of one adnasal lobe (measured at base), fringed by setae. Ventral surface (Fig. 5B) smooth except long setae on lateral margins and few shorter setae along outer edge of ventral ridges; ventral ridges almost reaching anterior margin; gular region probably with two sutures (sulci).

Antenna (Figs. 2C and 5C) with three antennomeres, sparsely setose; basal antennomere about 1.2 times as long as median one; median antennomere 1.8 times as long as apical one; apex of median antennomere with minute dome-shaped sensorium lateroventrally; apical antennomere with one long seta and a few short stiff setae. Mandible (Figs. 2A,B, 4A,B, and 5A,B,I) about twice as long as wide, narrow, unidentate, incisor edge with small retinaculum, lateral surface of basal half concave, penicillus not visible; one seta dorsolaterally and few setae near apex.

Maxilla (Figs. 2B and 5B) with stipites 3.3 times as long as wide, gradually narrowed posteriorly, almost contiguous at base, anterior margin narrowed and membranous; lateral margin with sparse punctures, few long setae on anterior corner; maxillary palp four-segmented, elongate, sparsely setose, palpomere I as long as palpomere II, palpomere III 1.3 times as long as palpomere II, palpomere IV 0.7 times as long as palpomere III; galea palpiform, two-segmented; lacinia possibly reduced to densely setose area; cardines hidden.

Labium (Figs. 2B and 5B) with prementum trapezoidal, 1.3 times as wide as long, weakly sclerotized, with a pair of long setae near anterior margin; postmentum elongate, triangular, membranous anteriorly; two pairs of punctures anteriorly and medially (setae missing), apex with two long setae; palp 2-segmented, elongate, apical palpomere strongly tapered, basal palpomere 2.3 times longer than apical palpomere.

Prothorax (Figs. 1A–D and 3B) 1.3–1.4 times as wide as long, about twice as long as mesothorax; mesothorax 2.7–2.9 times as wide as long; mesothorax and metathorax (Fig. 3A) subequal in size; pronotum with 2–3 long setae at anterior and posterior corners and a pair of shorter setae dorsolaterally near posterior margin, prosternum (Figs. 3B and 5D) twice wider than long, triangular; meso- and metathorax with 2–3 long setae laterally and one pair of setae dorsolaterally at posterior third. Leg (Figs. 3C and 5E) with sparse short to long

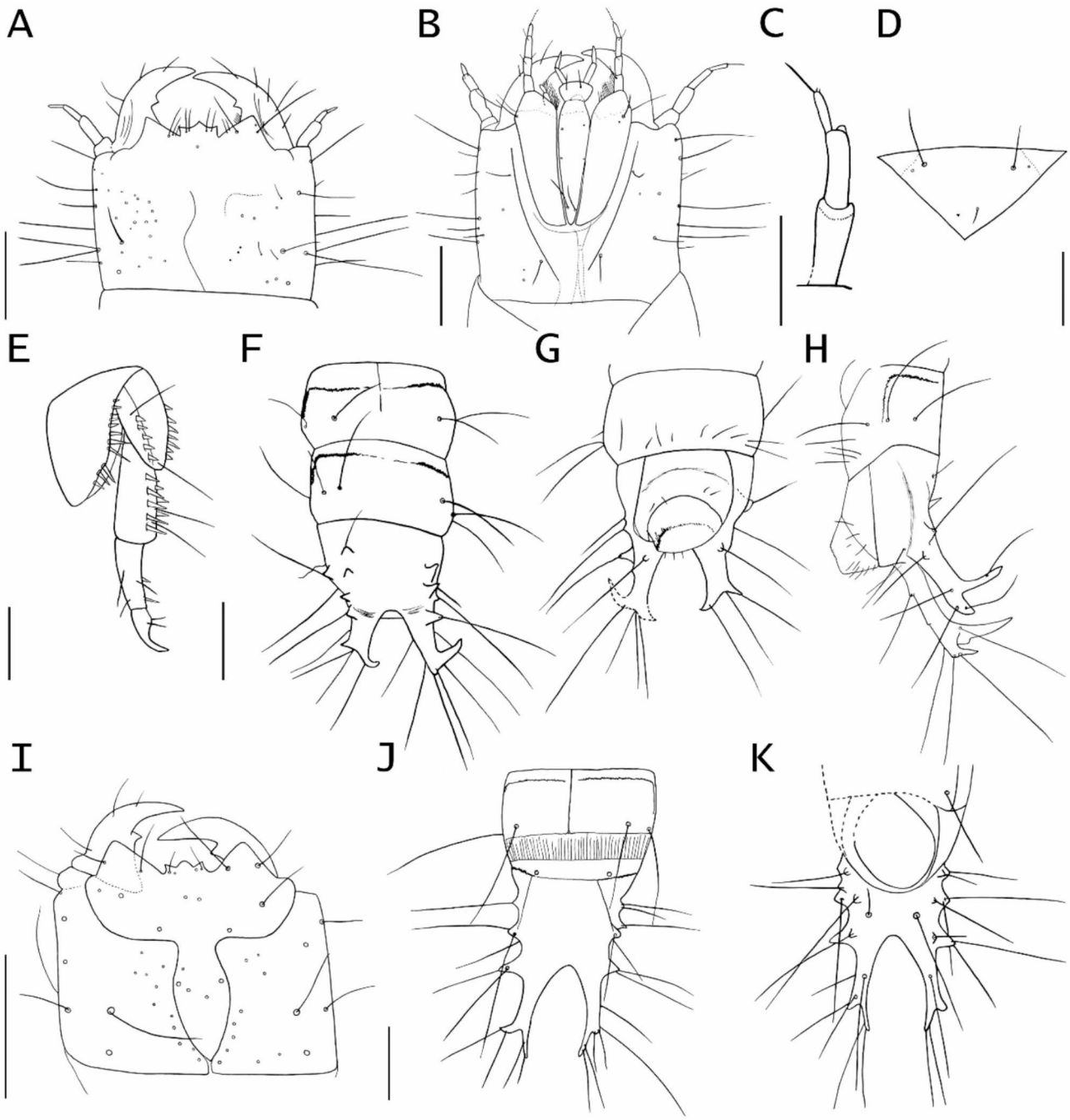


Fig. 5. Drawings of body parts of click beetle larvae from Burmese amber. (**A**–**H**) Specimen NM-T3536. (**A**) Head; dorsal view. (**B**) Head; ventral view. (**C**) Left antenna; dorsal view. (**D**) Prosternum; ventral view. (**E**) Right proleg; ventral view. (**F**) Abdominal segments VII–IX; dorsal view. (**G**) Abdominal segments VIII–X; ventral view (**H**) Abdominal segments VIII–X; lateral view. (**I**–**K**) Specimen NM-T3537. (**I**) Head; dorsal view. (**J**) Abdominal segments VIII–IX; dorsal view. (**K**) Abdominal segments IX–X; ventral view. Scale bars: (**A**–**B**, **D**–**K**) 1.0 mm, (**C**) 0.5 mm.

fine setae, strongly sclerotized short spine-like setae along two lateroventral rows; pretarsus slender with two setae at inner base.

Abdomen (Fig. 1A–D) subparallel up to segment VII, slightly narrowed apically; terga I–VIII divided into medio- and laterotergites, all mediotergites (dorsal sclerotized regions) with each side near posterior margin with two long setae laterally and one long seta dorsolaterally, ventral surface of segments I–VIII with row of setae on posterior margin. Segment IX (Figs. 2D–F, 4C–E and 5F–H,J,K) with tergum undivided, extending ventrally around posterior and lateral parts of segment X, dorsal region flat, without elevated borders, sparsely punctate, lateral margin posteriorly with row of three spine-like tubercles (teeth) increasing in length posterad, each

Tribe	Parablacini			Pityobiini	Tibionemini		
Genus/species	*Metablax acutipennis*	African unknown genus	Australian unknown genus	*Pityobius anguinus*	*Tibionema abdominalis*	New Zealand unknown genus	Burmese amber unknown genus
Sides of head	Subparallel	Subparallel	Subparallel	Subparallel	Subparallel	Subparallel	Subparallel
Antennal sensorium, shape	Dome-shaped	Dome-shaped	Dome-shaped	Dome-shaped	Dome-shaped	Dome-shaped	Dome-shaped
Postmentum, shape	Triangular	Triangular	Triangular	triangular	Triangular	Triangular	Triangular
Retinaculum	Present	Present	Present	Present	Present	Present	Present
Mandible, number of teeth	1	1	1	2	1	1	1
Adnasalia length/nasale length	Equal	Equal	Equal	Shorter	Longer	Longer	Longer
Adnasalia distance/adnasalium lobe width	< 1 (approximate)	< 1 (approximate)	< 1 (approximate)	> 1 (widely separated)	< 1 (approximate)	< 1 (approximate)	< 1 (approximate)
Nasal teeth	3	3	3	4	3	3	3
Gular region	One longitudinal sulcus	One longitudinal sulcus	One longitudinal sulcus	One longitudinal sulcus	Pair of longitudinal sulci	Pair of longitudinal sulci	Pair of longitudinal sulci (probably)
Mediotergites with pigmented impressions	Present	Present	Present	Absent	Present	Present	Present
Segment IX, teeth on lateral margin	Present	Present	Present	Present	Present	Present	Present
Urogomphus, inner prong	Directed upward and slightly inward	Directed upward and slightly forward	Directed upward and slightly inward	Directed upward	Directed slightly inward and posteriad	Directed upward and slightly inward	Directed upward or posteriad
Lateral area of tergum IX as sclerotized and pigmented as dorsal part	No	No	No	No	Yes	Yes	Yes
Transverse carina on sternum IX	Present	Present	Present	Present	Absent	Absent	Absent
Median longitudinal suture on anterior portion of sternum IX	Present	Present	Present	Present	Absent	Absent	Absent
Anal hooks	Absent	Absent	Absent	Absent	Absent	Absent	Absent

Table 1. Overview of the principal diagnostic morphological characters of larval Pityobiinae.

bearing one long seta; laterodorsal and lateroventral regions with small tubercles with long setae; urogomphi long, about 0.8 times as long as basal part of segment IX, bifurcate in two sharp prongs, each bearing 1–3 long setae, outer prongs either slightly longer than inner prongs (NM-T3537) or distinctly longer than inner prongs (NM-T3536), outer prongs either bent upward at slightly more than 45 degrees (NM-T3537) or at almost 90 degrees (NM-T3536), inner prongs either bent upward at about 45 degrees (NM-T3536) or oriented posteriad (NM-T3537); ventral surface of each urogomphus with one seta arising from minute tubercle; sternum IX with anterior part membranous, without transverse carina. Segment X (Figs. 2E,F, 4D,E and 5G,H,K) conical, ventral, membranous, with few fine setae, without anal hooks.

Remarks. Two here examined larvae are very similar to each other so that the most characters given in the description are present in both of them; however, the details of the ventral head, mouthparts, and sterna are based on the specimen NM-T3536 only, because those parts are either not present (ventral head, including mouthparts) or not well visible on the specimen NM-T3537. Those features, however, usually do not vary among species of the same genus. We unambiguously consider both larvae belonging to a single genus. However, there is a question if they also represent two younger instars (possibly first and second) of the same species or if they belong to two different species. Specimen NM-T3537 is about 9 mm long and 1.1 mm wide, while specimen NM-T3536 is about 9.5 mm long and 1.6 mm wide when measured at the widest place. If these are the only differences, we would consider both larvae being different younger instars of the same species. However, they substantially differ in the relative lengths of inner and outer prongs of urogomphi and their orientation, which could be a difference between two species. Therefore, we keep open the question whether the here-examined larvae represent a single species or not.

Discussion

The first possible larva of Elateridae from the Upper Cretaceous Burmese amber was recently reported by Zippel et al.[52]; however, no subfamily-level characters are well visible on that specimen, making its systematic placement unclear. Despite this fact, Zippel et al.[52] interpreted it as a possible member of Elaterinae, stating that "the overall arrangement of the antennae and mouthparts, although only seen in antero-lateral view, is strongly resembling that in modern larvae of Elaterinae". The here-examined two larval specimens, however, have different morphology (Figs. 1, 2, 3, 4 and 5) and represent another subgroup of click beetles, Pityobiinae (sensu Motyka et al.[31]). Based on the general shape and sclerotization of the body, they also remind larvae of Agrypninae and share some characters with Dendrometrinae.

The newly reported larvae from Burmese amber share with Agrypninae and Pityobiinae a dorsoventrally flattened body, more flattened on head and prothorax, the cuticle of head and prothorax more sclerotized than abdomen, the ventral surface of abdomen less sclerotized than the dorsal surface, the labium with postmentum triangular, the apices of maxillary stipites approximate, the prosternum undivided, the segment IX with a notch at apex, and a pair of urogomphi[46,53]. However, the fossil larvae differ from Agrypninae in having the mandibles with retinaculum, the antennal sensorium dome-shaped, the mesonotum, metanotum and abdominal mediotergites

I–VIII with prominent pigmented impressions, and anal hooks absent. Agrypninae usually lack retinaculum (with the exception of *Meristhus (Sulcimerus) niponensis* Lewis) as well as the mediotergite impressions, and have the antennal sensorium conical and, with some exceptions in Hemirhipini, have anal hooks[44–46,56,57].

The Burmese amber larvae share with Dendrometrinae (and also with all known Pityobiinae with an exception of genus *Pityobius*) the mandibles with retinaculum, the adnasalia approximate and longer than nasale, the paired pigmented impressions extending mesally in about 90 degrees angle on mesonotum, metanotum and abdominal mediotergites, the ventral surface of segment IX with setae arising from minute to prominent tubercles, the caudal notch separating two urogomphi, and segment X without anal hooks[44,45,58–61]. Dendrometrinae and Pityobiinae have also mediotergite IX with a dorsal plate delimited anteriorly and laterally by an elevated and carinate border marginated by a row of prominent tubercles; however, the dorsal plate is indistinct in the fossil specimens, nevertheless a carina on anterior and lateral borders seems to be present in the specimen NM-T3537 (Fig. 4C). On the other hand, Dendrometrinae larvae clearly differ from here-examined fossil larvae as well as from recent Pityobiinae[53] in having the body evenly sclerotized (versus progressively less sclerotized segments from mesonotum to abdominal segment VIII), the antennal sensorium long, 1/3 or more of the apical antennomere length (versus very small and short), the apical setae on antennomere 3 short and subequal (versus one very long seta), the postmentum subparallel-sided (versus triangular), and the caudal notch usually almost circular (sometimes lozenge-shaped) due to inner prongs of urogomphi being strongly directed inward (versus U- or V-shaped notch and urogomphal inner prongs bent upward, posteriad or only slightly inward).

Based on the available morphological evidence we place two newly reported larvae unequivocally in the small subfamily Pityobiinae. Hyslop[43] originally erected tribe Pityobiini for a single North American genus *Pityobius* primarily based on larval characters. Hyslop classified it in his "Pyrophorinae" based mainly on the presence of the paired urogomphi, separating it from other groups currently classified in Agrypninae, Dendrometrinae and Oestodinae by the additional combination of anal hooks lacking, postmentum triangular, and mandibles with three teeth (i.e., two apical teeth and a retinaculum). Later authors added several genera from New Zealand, South America and Australia, including unassociated larvae from South Africa[30,31,47,53,62–64]. Dolin[63] defined the Pityobiinae larvae as having retinaculum, postmentum triangular, stipites joined by their bases, cardo with one sclerite, galea two-segmented, head and prothorax heavily sclerotized and remaining segments leathery, and segment IX notched. Ulrich[53] examined the larval morphology of Pityobiinae in detail, improved their diagnosis, and divided the group into Pityobiini (*Pityobius*, *Metablax* Candèze pars and unassociated species from Australia and South Africa) and Tibionemini (*Tibionema*, and an unassociated New Zealand species). Ulrich's larval diagnosis of Pityobiinae includes the abdominal segment IX with paired urogomphi, the postmentum triangular, the anal hooks absent, the anterior margin of sternum IX sclerotized and pigmented, forming a divided transverse carina (absent in Tibionemini), the cardines divided into four sclerites, and the antennal sensorium dome-shaped, arising from a circular, sclerotized base[53]. Except for the division of the cardines into four sclerites, which cannot be observed in fossil specimens, the Burmese amber larvae share all of these features but the presence of a transverse carina on sternum IX.

The recent phylogenetic analyses placed Pityobiinae in a clade with Hapatesinae from Australasia[30,31,41] (Fig. 6). Larva of *Hapatesus* Candèze shares some features with Pityobiinae, including the presence of retinaculum and absence of anal hooks, and especially with the Southern Hemisphere groups, including the fossils, with which they share approximate adnasalia, tridentate nasale, and prominent pigmented impressions on thoracic and abdominal mediotergites[53,65]. Nevertheless, the *Hapatesus* larva bears unique features such as the rounded sides of the head, the parallel-sided postmentum, the absence of laterodorsal prominent teeth (tubercles) or any tuberculate setae on lateral and ventral parts of segment IX, the dorsal plate on segment IX without elevated and carinate borders, and the inner prongs of urogomphi strongly directed inward[65,66].

Pityobiinae as currently defined[31] are classified into four tribes, i.e., Pityobiini (*Pityobius* from North America, *Cretopityobius* from Burmese amber), Tibionemini (*Tibionema* from South America, unassociated larva from New Zealand), Parablacini (several genera from Australia, New Zealand, South America, and unassociated larvae from South Africa), and Campyloxenini (bioluminescent *Campyloxenus* Fairmaire & Germain and *Malalcahuello* Arias-Bohart from South America) (Fig. 6; Table 2). It should be noted that two latter tribes were separate subfamilies until recently and that there is no information on immature stages for Campyloxenini[31,39]. Larval Pityobiini strikingly differ from the here-examined Burmese amber larvae in having bidentate mandibles, nasale with four teeth, adnasalia widely separate and shorter than nasale, disticardines absent, labial sclerite fused, gular sulcus short, postgular sclerite long, pigmented impressions on mediotergites and dorsal plate on tergum IX less distinct, without elevated and carinate borders[43,53,67]. Parablacini larvae differ from fossil larvae in having the adnasalia as long as nasale, the transverse carina on sternum IX, and the lateral region of tergum IX not as sclerotized and heavily pigmented as a dorsal region[53,54].

Our Burmese-amber larvae are most similar to Tibionemini (Table 1), with which they share unidentate mandibles, tridentate nasale, approximate adnasalia which are longer than nasale, the lateral region of tergum IX as sclerotized and heavily pigmented as a dorsal region, the absence of a transverse carina on sternum IX, and the anterior portion of sternum IX entire, not divided by longitudinal suture[53,55]. According to Ulrich[53], Tibionemini contain two species, i.e., the only formally described *Tibionema abdominale* (Guérin-Méneville) from Chile and an unassociated larva from New Zealand, previously erroneously associated to *Metablax*, a genus in Parablacini. The fossil larvae from Burmese amber are morphologically more similar to the New Zealand larva by the posterior set of long setae on abdominal mediotergites, with each mediotergite bearing two lateral setae and one dorsolateral seta (several setae along anterior margin in *Tibionema*). Tibionemini were found to be a sister-group of Campyloxenini in a recent phylogenetic analysis[31]. Since the larvae of Campyloxenini have not yet been described, we cannot exclude the possibility that our fossil larvae are in fact members of Campyloxenini or the stem group of Campyloxenini + Tibionemini. According to Motyka et al.[31], these two tribes originated at

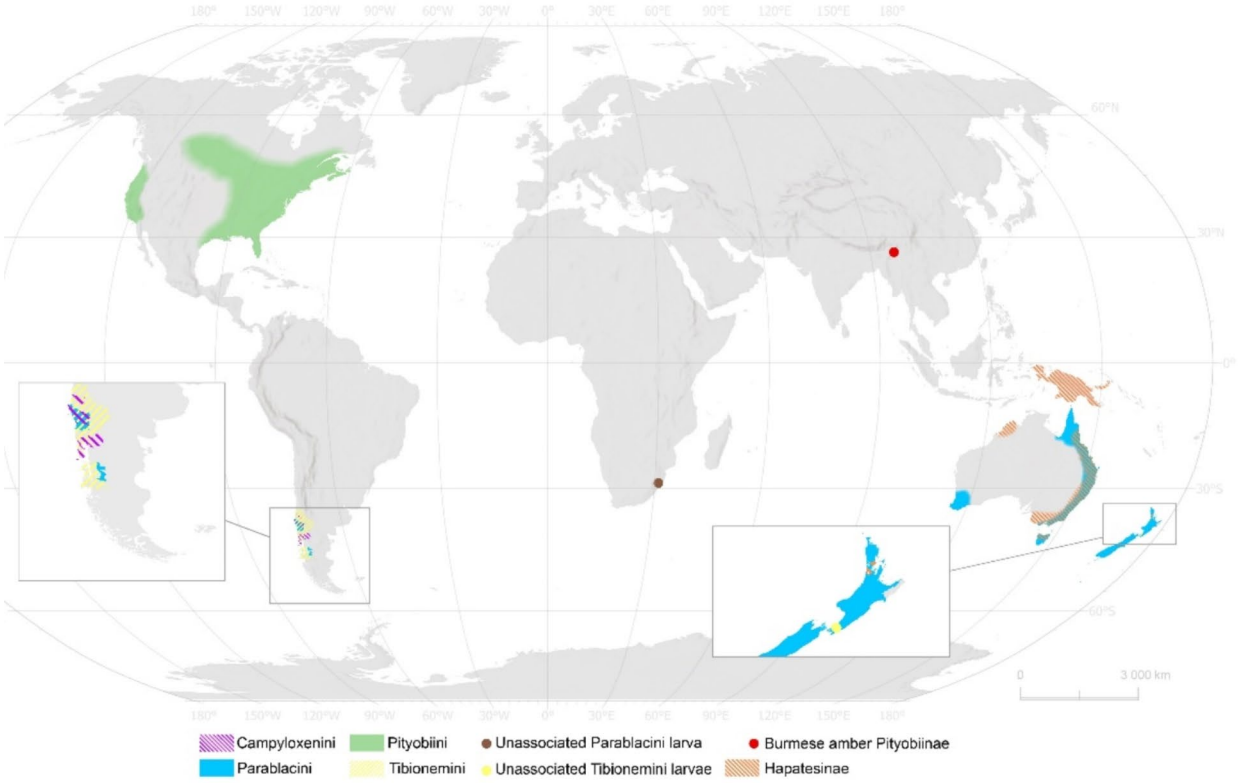


Fig. 6. Distribution map of Pityobiinae and Hapatesinae, including the fossil records.

Tribe	Genus	spp.	Distribution
Pityobiini Hyslop, 1917	*Pityobius* LeConte, 1853	2	Canada, USA
	†*Cretopityobius* Otto, 2019	1	Cretaceous Burmese amber
Parablacini Kundrata et al., 2016	*Elatichrosis* Hyslop, 1921	13+	Australia (incl. Tasmania)
	Metablax Candèze, 1869	5	New Zealand
	Ophidius Candèze, 1863	4	Australia
	Parablax Schwarz, 1906	9+	Australia (incl. Tasmania)
	Parasaphes Candèze, 1882	1+	Australia
	Rousia Calder, 1996	1+	Australia
	Sharon Arias-Bohart & Elgueta, 2015	2	Chile
	Tasmanelater Calder, 1996	1	Australia (Tasmania)
	Wynarka Calder, 1996	1	Australia
	Xuthelater Calder, 1996	1	Australia
	unknown genus	2?	South Africa
Campyloxenini Costa, 1975	*Campyloxenus* Fairmaire & Germain, 1860	1	Argentina, Chile
	Malalcahuello Arias-Bohart, 2015	1	Chile
Tibionemini Motyka et al., 2023	*Tibionema* Solier, 1851	1	Argentina, Chile
	unknown genus	1	New Zealand
	†unknown genus	1 or 2	Cretaceous Burmese amber

Table 2. Overview of the Pityobiinae diversity and distribution. Extinct taxa are marked with "†". Number of species under described genera means only described species, "+" denotes additional known undescribed species.

~ 96 Mya, while Burmese amber is dated to 99 Mya[9]. The morphological descriptions of larvae of Campyloxenini are crucial for further conclusions.

The Burmese larvae differ from all other Pityobiinae in their longer body vestiture, the antennae, maxillary palpi, labial palpi and urogomphi being relatively slender and longer, and the segment IX having its dorsal surface rather flat and without elevated edges. However, at least some of these characters may be related to differences between younger and older larval instars, as the fossil larvae certainly represent younger larvae (at least specimen NM-T3537 is possibly the first instar). First-instar larvae of Elateridae usually have sparser and longer body vestiture and the abdominal apical notch can be longer and narrower, forming longer and slenderer urogomphi[58,68,69]).

The fossil record of Pityobiinae includes so far only a single recently described monotypic genus, i.e., *Cretopityobius* Otto from Burmese amber[70]. This taxon shared the general appearance and some characters, e.g., the biflabellate antennae, with the North American *Pityobius* and was included in the tribe Pityobiini by Motyka et al.[31]. This would mean our fossil larvae from the same deposit, being tentatively classified in Tibionemini, are not congeneric with *Cretopityobius*; however, the placement of the latter needs thorough examination when more material is available. Therefore, we keep open the question whether the fossil larvae reported in our study can be congeneric with *Cretopityobius* or not. It should be noted, that except for the pityobiine *Cretopityobius*, only representatives of Agrypninae (one species), Dendrometrinae (one species) and Elaterinae (four species) have been formally described to date from Burmese amber, with two additional species being classified as *incertae sedis* but morphologically very different from Pityobiinae[51]. Considering a high number of still undescribed elaterid taxa from Burmese amber (RK, pers. observ.), it is likely that the larvae belong to a yet undiscovered taxon (although the *Cretopityobius* hypothesis is still on the table).

There is an ongoing debate about the origin of Burmese amber and its biota, and the principal questions are where exactly was the Burma Terrane at the time of the amber formation and deposition, and if the bioinclusions trapped in Burmese amber were of a Gondwanan or a South East Asian origin[21,23,26–28,71]. There is a more or less accepted hypothesis that at the time of the amber deposition, the Burma Terrane was an isolated island drifting northward[22]. Recently, dramatically increased number of studies documenting biota of Burmese amber[8] brought some interesting insights about its affinities to either Laurasia or Gondwana. Increasing number of discoveries suggest that the Burmese amber insects often have Gondwanan affinities, especially with Australian and Neotropical regions[26–28,72–82]. Most recent study by Wood & Wunderlich[83] not only provided further evidence that the Burmese amber fauna has ties to Gondwana but they also suggested that the Burma Terrane served as a biotic ferry transporting specimens from Gondwana to the Northern Hemisphere, similar to what has been suggested for the Indian Plate. On the other hand, some other authors report Burmese amber taxa had their close relatives in Laurasia[29,84,85], and, more importantly, Peris & Jelínek[86] argued that there are many examples of taxa found in various Cretaceous ambers (e.g., from France, Spain, or Canada) whose current relatives are found exclusively in Australasian and Neotropical realms, and which do not have a Gondwanan origin (see also Peris et al.[87]). They attributed the differences between modern and past distributions of many taxa to changes in the vegetation and the wider distribution of the forests found in the Southern hemisphere during the Cretaceous[86]. It is becoming more and more evident that Burmese amber contains lineages from both landmasses, and there are various hypotheses why either Gondwanan or Laurasian fauna was present in the tropical amber forest of Burma Terrane (some taxa were previously widely distributed but recently have a relict southern distribution, some taxa could have flown from Asia to the Burma Terrane when it was still an island but relatively close to the Laurasian coast, etc[22,83,88,89]). Since the Burma Terrane was likely an isolated island for large periods of time, numerous taxa were probably also island endemics. This hypothesis is confirmed by numerous taxa being known exclusively from Burmese amber, including the insect families from various orders[90–95].

The pityobiine tribes Campyloxenini, Parablacini and Tibionemini, all with Southern Hemisphere distributions (Table 2; Fig. 6), were suggested to have a Gondwanan origin by previous study[31]. On the other hand, Pityobiini, with the recent species occurring in North America and *Cretopityobius* known from Burmese amber, may have been more widely distributed in the past. Further research should be focused on *Cretopityobius*, as its proper systematic placement is crucial for understanding the diversity, distribution and evolution of the interesting click beetle lineage which supposedly might have originated in Gondwana and contain a recent bioluminescent lineage[31].

Materials and methods

This study is based on two larval specimens entombed in amber. They were bought from a commercial fossil dealer by the first author. To our knowledge, both examined amber pieces were mined and sourced before June 2017. They are deposited in the collection of the Department of Palaeontology of the National Museum, Prague, Czech Republic (NMPC). The amber pieces were already polished before we examined them, and later (post-acquisition) they were only very slightly polished by hand, which allowed improved views of the included specimens. The amber pieces were not subjected to any supplemental fixation. Observations of the specimens were made using an Olympus SZX12 stereomicroscope, and the photographs (Figs. 1, 2, 3 and 4) were taken using a Canon EOS M6 Mark II camera mounted on a stereomicroscope. The amber piece was submerged in glycerine during imaging to improve light dispersion and reduce reflections. Stacks of photographs were combined with the software Helicon Focus Pro (version 7.6.4, Kharkiv, Ukraine), applying the rendering method 'depth map' or 'weighted average'. Adobe Photoshop CC (version 2019-20.0.5) was used for the contrast enhancing. Line drawings (Fig. 5) were made based on photographs and revised upon detailed specimen examination under stereomicroscope. The measurements were taken with a scale bar in an eyepiece. Body length of both examined specimens was measured from the nasale to the apex of urogomphi, and the body width was measured at the widest part. Morphological terminology follows partly Costa et al.[35], Ulrich[53], and Glen[58], and the classification of Pityobiinae follows Motyka et al.[31]. The distributional map of Pityobiinae and Hapatesinae (Fig. 6) was created

using ArcGIS Pro 3.0 and GIMP 2.10.36 (GNU Image Manipulation Program), with data coming from Natural Earth (https://www.naturalearthdata.com) and Esri Living Atlas of the World (https://livingatlas.arcgis.com). Distribution estimation is based on data published in literature[47,53,54,96–101] and/or available from publicly available internet sources (GBIF; www.gbif.org; iNaturalist, www.inaturalist.org). The spatial distribution is portrayed by blurring to visualize a certain degree of uncertainty[102]. The ZooBank LSID number for this publication is: urn:lsid:zoobank.org:pub:54CF94C4-7442-400B-88C9-C2AAF7CB3B5D.

Data availability

All data needed to evaluate the conclusions in the paper are present in the paper. The high resolution photographs of the examined specimens are available from the corresponding author upon reasonable request.

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Author Statement

This is to declare that we would support repatriation efforts and the future return of the examined specimens to Myanmar for deposition and curation in an appropriate public institutional collection.

Author contributions

R.K. conceived and designed the study. K.T. and R.K. prepared amber pieces, made photographs, and created figure plates. S.P.R. (lead) and R.K. carried out the morphological investigation. S.P.R. prepared line drawings. J.B. (lead), R.K. and J.H. prepared the distributional map. R.K. (lead) and S.P.R. wrote the initial manuscript with help of G.P. All authors performed the literature search, discussed the results, and edited, reviewed and approved the manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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APPENDIX 6

Intuitiveness of geospatial uncertainty visualizations: a user study on point symbols

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Intuitiveness of geospatial uncertainty visualizations: a user study on point symbols

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ABSTRACT The understanding of uncertainty, or the difference between a real geographic phenomenon and the user's understanding of that phenomenon, is essential for those who work with spatial data. From this perspective, map symbols can be used as a tool for providing information about the level of uncertainty. Nevertheless, communicating uncertainty to the user in this way can be a challenging task. The main aim of the paper is to propose intuitive symbols to represent uncertainty. This goal is achieved by user testing of specially compiled point symbol sets. Emphasis is given to the intuitiveness and easy interpretation of proposed symbols. Symbols are part of a user-centered eye-tracking experiment designed to evaluate the suitability of the proposed solutions. Eye-tracking data is analyzed to determine the subject's performance in reading the map symbols. The analyses include the evaluation of observed parameters, user preferences, and cognitive metrics. Based on these, the most appropriate methods for designing point symbols are recommended and discussed.

KEY WORDS uncertainty – maps – eye-tracking – symbol set – visual perception – data quality

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1. Introduction

Even when spatial data are well described, users may not be aware of the inherent uncertainty in all the datasets they use. For this reason, it is crucial to evaluate the results of the analysis based on this data to understand the validity, limitations and conclusions. Moreover, many map readers, when they view a map based on results of spatial analysis, modeling or data manipulation, fail to understand that those results are affected by uncertainty. It is therefore of primary importance to design symbols and geovisualizations in a way which the user will intuitively understand. This problem is addressed in several research papers (Berjawi et al. 2014; Finger, Bisantz 2002; MacEachren et al. 2012). In addition, there has been significant research activity focused on visualizing uncertainty in particular detail. However, the use of such techniques in practice is still rare because standardized methods and guidelines are few and mostly untested. Nevertheless, the authors mentioned above do not take into consideration the measures available based on eye-tracking experiments. Therefore, our main ambition is to investigate, via eye-tracking, how individual symbol sets work on the map during reading tasks. We aim to bring new research findings to extend already published studies and to address several research questions: Is there any connection between user preferences and the effectiveness of symbols? Does the visual variable affect the perception of point symbols? Are there differences in the form of legends for point symbols? Can Geographic Information Science (GIScience) education change user interpretation (or preferences) or symbol effectiveness?

2. Background

2.1. The term uncertainty

Uncertainty implies that there is something we are not sure of in spatial data and analysis due to various reasons, such as ignorance of human knowledge, a generalization of geographic features, measurement errors, and incomplete representation of all factors in the analysis (Li 2017). A practical example where uncertainty has to be taken into consideration can be the delimitation of zones based on spatial data modeling (Machar et al. 2017; Pechanec, Burian, Kiliánová 2011). In our work, the definition by Longley et al. (2005) is adopted: "Uncertainty is the difference between a real geographic phenomenon and the user's understanding of the geographic phenomenon." It is distinct from concepts such as error or accuracy because it acknowledges an unknowable component of all geospatial information. For example, positional accuracy refers to the absolute and relative accuracy of the positions of geographic features. Attribute accuracy refers

to the accuracy of the quantitative and qualitative information attached to each feature, and temporal accuracy refers to the coincidence between registered and actual time coordinate for the event. From our research perspective, the typology of uncertainty defined by MacEachren et al. (2005) is also essential, as it has received significant attention in the cartographic community. It can be used within the application of positional, temporal, and attribute uncertainties in geospatial data (Kinkeldey, Senaratne 2018). According to Brus (2014) the concept of uncertainty can be defined as the imperfection of users' knowledge about data, processes, or results. The uncertainties in spatial data and its analysis result from four major factors: (i) inherent uncertainty in the real world, (ii) the limitation of human knowledge in cognition of the real world, (iii) the limitation of the measurement technologies for obtaining spatial data, and (iv) the potential of generating and propagating uncertainty in the spatial data processing and analysis (Shi 2010).

In parallel with uncertainty, spatial data quality can be defined. There is now considerable agreement on the definition of quality in the literature, quality being defined as "fitness for use" (Veregin 1999). It can also be described as an evaluation of the similarity between spatial data and geographical truth, including both positional truth and attribute truth (Li 2017).

In the GIScience community, spatial data uncertainty has been a focus of research for the past several decades (Li 2017). In contrast with this statement was the concept of uncertainty in Czechia quite often neglected until last 10 years. This topic is of growing interest to the research community nowadays; we can find studies focused on cognitive aspects of uncertainty visualization (Kubíček, Šašinka, Stachoň 2014; Kubíček et al. 2017) or database quality (Hošková-Mayerová et al. 2013).

2.2. Visualization of uncertainty

Effective visualization should provide the appropriate visual metaphors to present information in a way that supports data comprehension. In this concept, data are primarily used to provide answers to specific questions, tests, hypotheses, or to explore relationships. In the case of GIScience, most of the data also have a spatial character, and the visual presentation must in this case also facilitate the achievement of the goals set. Most traditional visualization techniques have been created (and are often used), with the prerequisite that all available and user data are accurate and that the transfer of information is smooth. Even if there were a prerequisite in place, ensuring accurate, effective visualization of a data set, it would still be true that the displayed data contains a certain level of uncertainty (Brus, Pechanec, Machar 2018). In spite of these complications, the visualization of uncertainty as a way of communication can be traced back to initial studies dealing

with uncertainty in general (Beard, Buttenfield, Clapham 1991). Afterwards a wide variety of visualization algorithms were used for the visualization of uncertainties, including geographic information systems, meteorology, oceanography and medical research (Lermusiaux et al. 2006; MacEachren 1995; Pang 2001; Pang, Wittenbrink, Lodha 1997). Even though the view on the visualization of uncertainty changes and it is slowly coming into a growing range of studies, including those environmental ones, the implementation is still a very slow process and a problematic area (Brus, Voženílek, Popelka 2013). Consequently, the visualization of uncertainty remains one of the most important challenges of visual analysis (Wong et al. 2012). From the cognitive point of view it is necessary to take into account the main concepts as visual search (Egeth, Dagenbach 1991) and research dealing with scene under increased attentional load (Brand, Johnson 2014). From the visualization point of view, many classification schemes were proposed in the field of GIScience and Information Visualisation (InfoVis). Perhaps the most comprehensive overview can be found in MacEachren's work (2005). In contrast to the GIScience community less emphasis is placed on the formalization of uncertainty within the InfoVis community (Aipperspach 2006). In the InfoVis community, the concept proposed by Pang, Wittenbrink, Lodha (1997), which probably describes the issue best and most comprehensively from the perspective of the visualization of uncertainty itself, is most commonly referred to. This model is by its nature based on the visualization model proposed by Haber and McNabb (1990). The whole scheme is based on the need to visualize a real phenomenon, from the process of collection and transformation to the final visualization of the phenomenon. However, in the author's conception, the visualization scheme primarily relies on real phenomena more than on abstract phenomena. Despite this fact, the scheme is also generally applicable for the visualization of information within the GIScience domain. From this model, uncertainty spreads throughout the whole process. Accordingly, there has been significant research activity focused on visualizing uncertainty in detail. Multiple typologies have been proposed to identify and quantify relevant types of uncertainty and a multitude of techniques to visualize uncertainty have been developed (Potter, Rosen, Johnson 2012). Despite the high number of methods proposed; many questions related to the visualization of uncertainty remain unanswered. Due to the myriad techniques available for different types of data, there is a lack of a comprehensive overview of all the methods, complex typology and predominantly tools that can efficiently work with the visualization of uncertainty. The fact that there is a lack of detailed recommendations and methodology for selecting individual methods is crucial, moreover, the lack of methodologies proven to be supported by user testing is the bottleneck of the whole research area.

2.3. Existing empirical studies

Over the years, there has been an increase in the number of studies that evaluate (rather than categorize or suggest methods for) uncertainty visualization, but the numbers are generally small with some variability (Kinkeldey et al. 2017). From our research, the work of MacEachren et al. (2012) is fundamental. The authors did not just focus on building a symbol set for one particular purpose. Instead, they aimed to design symbols that could be used universally in maps, tables, and in other forms in various scientific disciplines. The objective is to create a standardized graphic form of symbols for the visualization of uncertainty. They created symbols sets to express time, spatial, and attribute accuracy. They revealed their level using variable parameters of individual symbols. Specifically, it was each symbols's placement, its size, color tone, value, texture, orientation, shape, transparency, fuzziness rate, and image resolution. The suitability of the proposed symbols for this purpose was subsequently tested in an experiment consisting of two parts. In the first part, symbols sets with three levels of uncertainty contained were created. These were subsequently submitted to the participants for assessment of the subjective perceived suitability. In this way, information about the effect of individual symbols on the reader was acquired. In the second part, matrices (3×3 symbols) with different levels of overall accuracy were assembled from each symbol set. These were subsequently submitted to the participants in pairs. His task was to determine the total uncertainty levels contained in the matrix and to select the one with the higher value. The evaluation was based on the correctness of the responses and the time that respondents needed to decide. Therefore, the practical suitability and interpretation demand factor of each symbol set was assessed. The variable parameters of the symbols that were perceived to be best included fuzziness, location, and value. However, when using these symbols, it is necessary to keep their logical level order, where the increasing uncertainty increases the value of the used parameter. In the experimental section about the practical use of symbols, the highest number of correct responses was recorded with the shortest decision time for fuzziness and value methods. Thus, in the overall comparison, it is possible to recommend fuzziness, location and value as the most appropriate methods for the representation of uncertainty.

Other authors who addressed the problem of the representation of spatial data uncertainty were Berjawi et al. (2014). Their study was focused on showing the points of interest (POI) on the map. Individual POI corresponded to hotels, restaurants, and other attractive tourist destinations, for which the location and attribute information were tracked. The need to express the quality of the information was based on a data acquisition algorithm. This algorithm browsed through various data sources from which it took information about a destination. This information was subsequently appropriately combined, and the completeness and consistency

of all the data obtained were evaluated. Based on this knowledge, the uncertainty was subsequently determined. The accuracy of location was determined based on Euclidean distance, an attribute based on the cluster analysis of similarity. Several symbol sets were created to represent the POI. Besides the newly designed ones, the best-rated symbols from the work of MacEachren et al. (2012) were used. They also examined a combination of multiple variable attributes to represent uncertainty within one symbol, such as location and fuzziness. If both correspond to one type of accuracy, then the possibility of misunderstanding the information quality levels is lowered. However, they can also be used to represent more types of accuracy in a one- symbol set, thereby increasing the information value, but at the cost of complicating the information acquisition process. In the test section, the symbols were first placed in pairs, which were then displayed in front of participants. Their task was to select a symbol with a higher level of accuracy. The assessment of the suitability of the symbol was based on monitoring the number of correct answers and the time needed for a decision. In the second part, the best-rated symbols were placed in the map to analyze the most appropriate form of how to represent the accuracy of the information, whether to use one symbol with a total accuracy level or more symbols corresponding to each type. The supplementation of an appropriate pop-up window was also tested. Based on the results, the option of one symbol set corresponding to the overall accuracy level with the sub-type displayed in the pop-up window was selected as the best. The map is not overloaded, while the maximum information value is maintained. Nevertheless, access to this data is more difficult.

3. Methodology

The study is based on the use of lessons learned from previous work aimed at the representation of point symbols to express the uncertainty. We followed the work of MacEachren et al. (2012) mainly by symbol set design. The whole workflow of the experiment is different. We perform one questionnaire with 100 respondents with a different background. We also mainly focus on simple questions about intuitiveness of designed symbols. In questionnaire we focused not only to point symbols but also to line and polygon ones and subsequently made several eye-tracking experiments. The whole finished study is nevertheless beyond the scope of a single paper and will be published in follow up work. The experiment reported in this paper is focused on point symbols consisting of an assembly of individual symbol sets suitable for expressing uncertainty. As already mentioned in addition to their assembly, their expected suitability was verified based on a questionnaire to determine perception and afterwards in practical use on the map. From this part of the experiment, information about symbol perception was obtained by

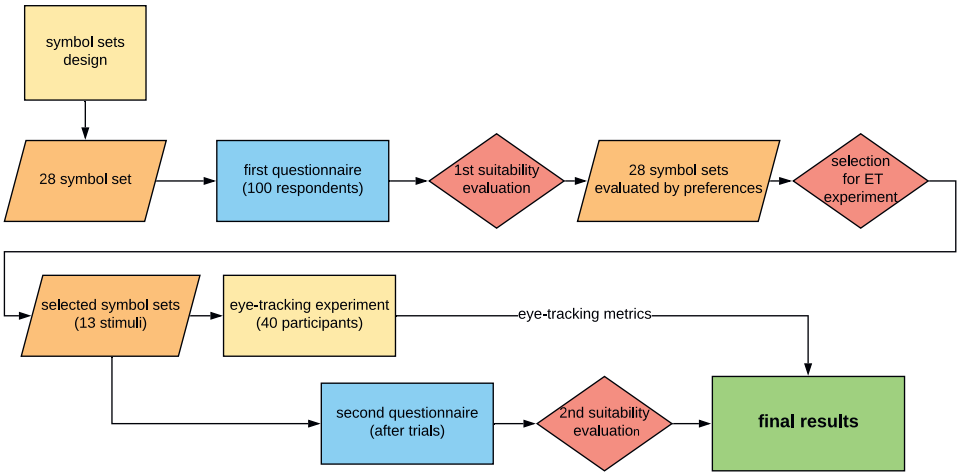


Fig. 1 – The design of the experiment

evaluating basic eye-tracking metrics such as scanpath length and trial duration. The eye-tracking experiment was conducted with a total of 40 respondents divided into two groups. The first group consisted of 20 students from the Department of Geoinformatics, Palacký University Olomouc who already had basic knowledge about the uncertainty of spatial phenomena. In this study, we considered them as cartographers. The second group consisted of 20 respondents without a GIScience background. We considered them as laypersons (non-cartographers). Answer choice was also used as a metric to assess whether the symbol set was correctly interpreted. Subsequently, the suitability was again evaluated via a second questionnaire. In addition to the symbols themselves, two variants of the legend were also proposed and the differences between respondents with and without GIScience background were observed. Our approach is therefore different from mentioned authors as we based our observation also on the eye-tracking experiment. This helps us to evaluate the real process of reading the map and gives a more realistic view of the process of getting information. The study design can be seen in Figure 1.

3.1. Symbol set design

At the beginning of the experiment, the symbol sets were designed to represent uncertainty. Their appearance was as already mentioned inspired by the results of the work done by MacEachren et al. (2012) and Berjawi et al. (2014). Initially 28 symbol sets were designed (Fig. 2). Symbol sets were created based on different

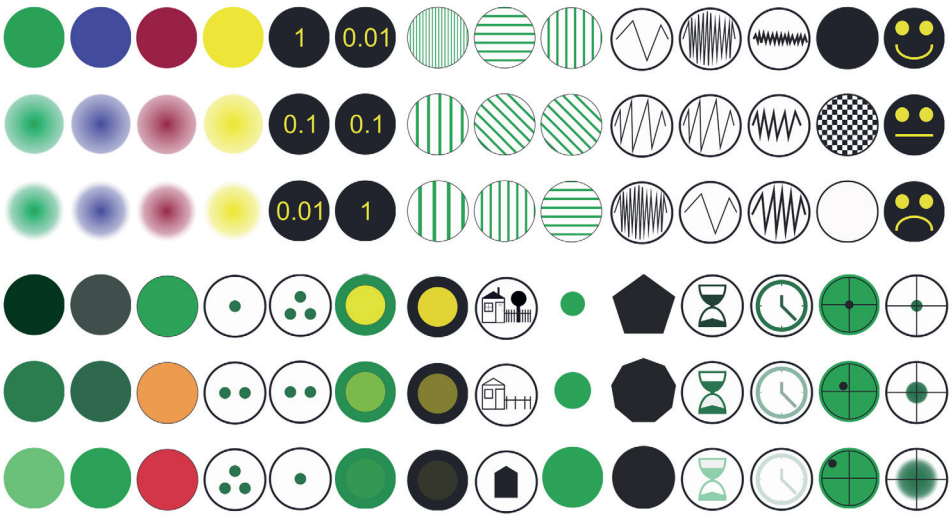


Fig. 2 – Main symbol set used in questionnaire (excluding modifications)

visual variable attributes to express uncertainty (fuzziness, size, saturation, color, and more). The selected sets were created in several color variations. Due to this, it was possible to compare the effect of the color preferences of the respondents on the result. Each symbol set represented three levels of uncertainty. Several point symbol sets were designed in two variants. This step was taken in consideration to verify the naturally perceived conjunction of the variable attribute level with a certain uncertainty level. In addition to the silhouette symbols also graphical forms were designed to measure differences in the perception of such symbol variations. The symbol sets can be also divided into groups showing different uncertainty issues (general uncertainty, accuracy, precision, and trustworthiness). Figure 3 shows a possible reflection of accuracy in the designed symbol sets. The symbols were designed for several followed-up eye-tracking experiments including combinations of symbols. In this paper, we introduce only one eye-tracking experiment, which focused on general uncertainty in a simple reading task.

3.2. Questionnaire

A questionnaire survey was put into the experiment to verify the suitability of the proposed symbol set before setup the eye-tracking experiment. The questionnaire was created in the Google Forms environment and contained 28 variants of point symbol sets with a corresponding legend of uncertainty level. In the questionnaire, each of them was also assigned a 7-point scale to express perceived suitability for

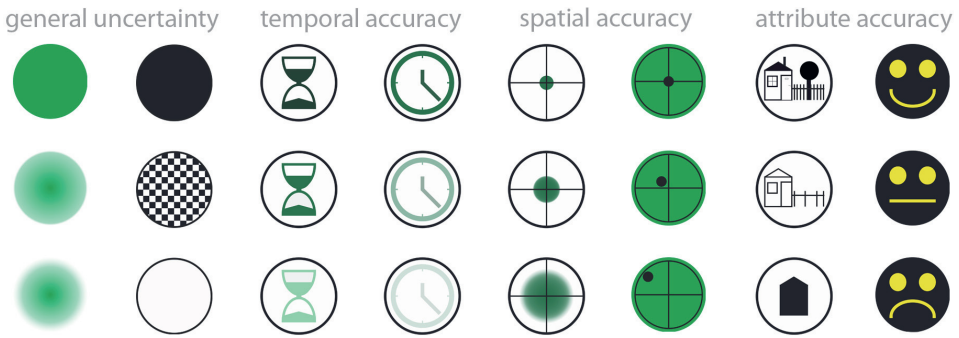


Fig. 3 – Reflection of accuracy in designed symbol sets

expressing uncertainty. The values vary on a scale from 1 to 7. Seven represented the maximum suitability. A detailed explanation of the term uncertainty was included in the introduction, as this term could have been unknown to some respondents. For many respondents, this was their first encounter with the term uncertainty. In addition, the questionnaire included several questions concerning respondent characterization. Namely, we asked for on age, gender, GIScience background including cartography and color perception deficiency. These personal oriented questions were on a voluntary basis. Information about possible congenital color perception deficiency was also included in the questionnaire.

3.3. Eye-tracking experiment

The main aim of the eye-tracking experiment was to verify whether the symbols with a high preference (suitability) score work in practical deployment. For the experiment, we chose highly preferred symbols, as well as those symbols with low scores. The aim of the experiment was to determine if low scored sets are also difficult to use during map reading tasks. All of these symbols were then placed in the map composition to illustrate the imaginary situation of the occurrence of a selected animal (fox). Figure 4 shows the finally selected symbol sets. In addition to the symbols, a legend was placed in the final stimuli. For testing, we designed two variants of legends: Variant "a" with uncertainty shown separately and variant "b" where uncertainty was incorporated directly in the symbol. The first one provides a simpler version, but in this case, the reader must apply the level of uncertainty to the symbol. However, its benefits may be noticeable in showing more phenomena, including information uncertainty expressed in a uniform style. In the second variant, the appearance of the symbol corresponding to individual levels of uncertainty is immediately apparent. Due to this, it is not possible to visualize some

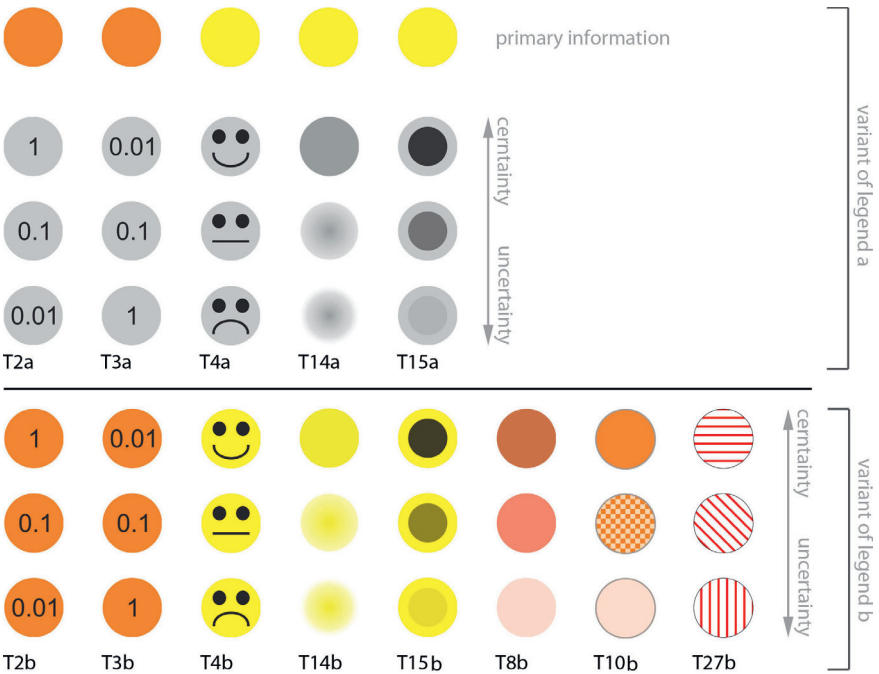


Fig. 4 – Symbol sets used in the eye-tracking experiment in two variants of the legend concept, variant a – the phenomenon and the uncertainty separately, variant b – a combination of both items of information

symbol sets using the method in variant "a". This is the reason why the number of symbol sets in variant "a" and "b" differs.

All map compositions used an orthoimage showing a forest landscape as the background. As we tried to incorporate the symbols in the map reading task, the chosen background helped us to minimize the complexity of map content. We avoided using topographic or thematic maps due to the mentioned map complexity and the possible influence of symbols by another map content. Moreover, to prevent its negative influence on the perception of the symbols themselves, the brightness and saturation of the colors were also adjusted. Before each stimulus (map), a sentence with a task to solve was shown to respondents.

3.4. "On the map choose the three most suitable locations to place the photo trap to record the occurrence of a fox"

The aim of the simple map reading task was to select places where the occurrence of the fox was likeliest. The respondents should incorporate uncertainty portrayed

by point symbol sets and select one location represented by symbols showing most certain data. SensoMotoric Instruments (SMI) RED 250 eye-tracker was used in the study. The eye-tracker was arranged in the department's eye-tracking laboratory. The stimuli were displayed on a 24-inch screen with a resolution of 1,920×1,200 pixels. Eye positions were recorded at a frequency of 250 Hz. Data were analyzed using the applications Open Gaze and Mouse Analyzer (OGAMA) and SMI BeGaze. We used "trial duration" which represents the total observation time of the stimulus. Based on its value, it is possible to reveal the difficulty of the task or evaluate the attractiveness of the stimulus. Another used metric was scanpath length, which describes the length of the gaze trajectory in pixels and can be used for similar purposes. Fixation count metric is also used in the study. This metric indicates how many fixations were recorded in a particular Area of Interest. Similarities between participants were analyzed using the ScanGraph tool. The tool was developed at Palacký University in Olomouc, Czechia and is intended to find out similarities and differences between respondent's strategy of stimuli inspection. It works using the principle of the String-Edit-Distance method of Scanpath Comparison (Doležalová, Popelka 2016; Popelka, Doležalová, Beitlová 2018). The total number of 40 participants can be considered sufficient – it is consistent with many other studies. For example, Incoul et al. (2015) compared paper and digital maps, and a total of 32 respondents took part in the experiment. A similar number of respondents was also used by Çöltekin, Fabrikant, Lacayo (2010) when comparing map interface, or Fuhrmann, Komogortsev, Tamir (2009) when searching for differences between the map and its holographic equivalent.

4. Results

4.1. Questionnaire survey

A questionnaire survey aimed at the subjective evaluation of individual symbol sets was completed by 100 respondents. The age structure of the respondents was 18 to 60 years, and according to the gender structure, there were 60 men and 40 women. The results of the individual sets were arranged according to the median of their ratings. This statistical indicator was chosen due to resistance to the extreme value influence effect and its higher suitability for describing an unknown distribution. If the median matched for multiple sets, then the assessment of the distribution of the obtained suitability values using 1st and 3rd quartile followed. The final ranking of the symbol is shown in Figure 5. The best rating symbol set group was "fuzzy". This variant of the symbol set was elaborated in 4 color versions (symbol sets S11, S12, S13, and S14). The aim of this step was the effort to assess the influence of color on the result of the perceived suitability. That

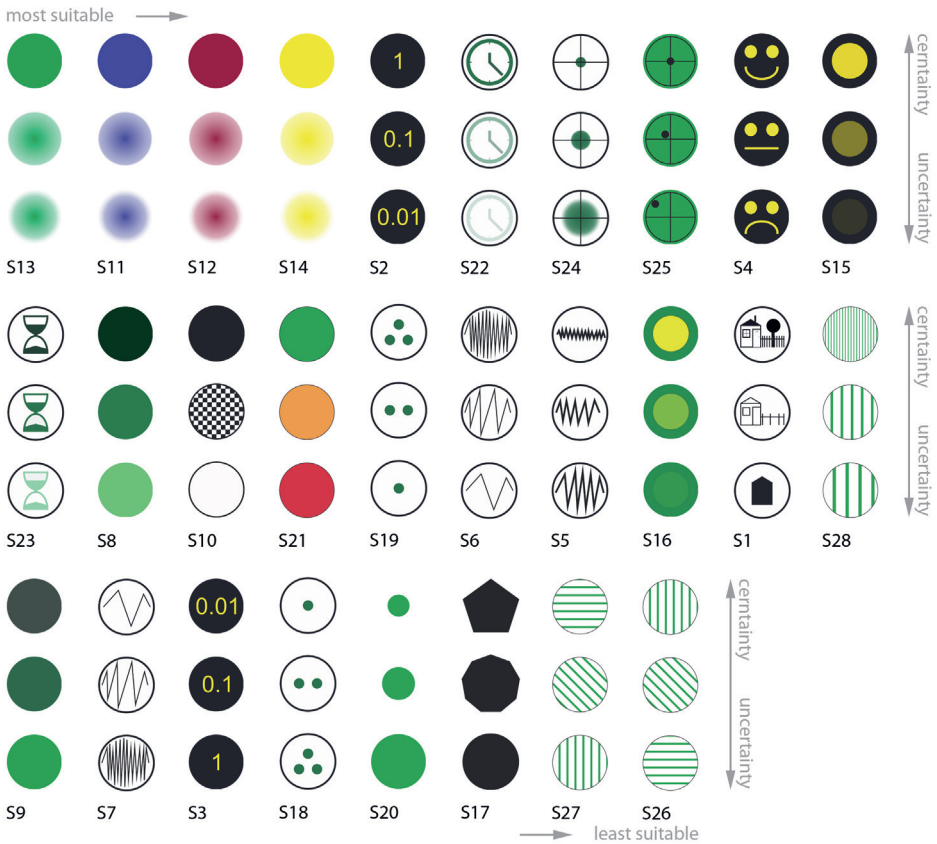


Fig. 5 – Final user rankings of the suitability of symbols from 1st questionnaire

is, whether the same symbols, just in a different color version, would be perceived differently. This hypothesis was not confirmed, and a similar result was achieved for all. Second most preferred was the symbol set S2. The uncertainty level is expressed by a numeric value located in the center of the symbol. The value of 1 corresponds to certain data and 0.01 to the uncertain data. The questionnaire also included a version which had the opposite uncertainty arrangement. This symbol set was not preferred and got the 23rd place. In the questionnaire, we also test symbols related to temporal accuracy. They were also evaluated as suitable. The S22 symbol only increases the transparency of the placed graphical form of the clock along with the increasing uncertainty. In addition to this variant, an hourglass version was also created with the identification S23 and was placed in 11th place.

Sets S24 and S25 were created for the positional uncertainty of the information. In the first variant, the accuracy in the space is induced using a variable point size. Its size should remind the reader of the localization in space. Therefore, with

a higher level of inaccuracy, it is necessary to define a larger search area. In the case of high accuracy, it is possible to determine the destination place in much more detail, and it is not necessary to define such a large search area. The second set of symbols expresses uncertainty using a variable distance between the center of the character and the point location. The center represents the maximum possible accuracy, and the more distant the point is, the more it decreases and at the same time the uncertainty increases. The S4 symbol set, which uses the symbol of the human face to represent the uncertainty was very popular among the participants in the research. This set evokes a human mood in the reader, namely cheerful, neutral and sadness, through a different style of the mouth. These attributes are assigned a level of uncertainty that can stimulate these feelings. Specifically, a low level of uncertainty corresponds to the cheerful face and a high level to sadness. Sets S4 to S22 achieved the same result in the overall ratings.

The set using transparency as the variable parameter was placed in 10th place. Compared with the S13 set, it is an advantage that the background does not affect its perception because the variable part of the symbol is placed on a monochrome surface. However, in this questionnaire, the symbol was not placed on the map background. Therefore, it was not possible to evaluate the potential influence of the background on this symbol set.

The eye-tracking data allowed us to evaluate several parameters quantitatively. The main parameter was the correctness and structure of the answers to the questions included in the experiment which indicate whether the set was understood correctly. Also, the respondent's cognitive analysis was performed by evaluating the time spent on the trial (*trial duration*), the map reading process, and the overall eye trajectory length within the stimulus (*scanpath length*). These parameters can identify the complexity of the set for understanding and its level of intuitiveness. To assess the suitability of each legend type, a comparison of the time of eye sighting to the area of its location was also performed. A more appropriate variant should be easier to understand and therefore the respondent should spend less time interacting with it.

Overall, symbol sets showing certain data were best evaluated (Fig. 6). In all cases except symbol sets T8b and T15a were most certain data represented by one occurrence only. The trials T8b and T15a included two of these points to assess whether this anomaly is reflected in the overall results. That is, whether respondents will look for another symbol that shows certain data once one has already been selected. Each respondent had the task of selecting the three most appropriate symbols overall, so he also had to complement his selection appropriately with the symbols carrying less quality information. The T2a set was the best evaluated symbols. The representation of these symbols in the overall selection was 33.3%. It can be said that this graphic form appears to be the most intuitive. This is evidenced by the very low number of selected symbols showing high uncertainty,

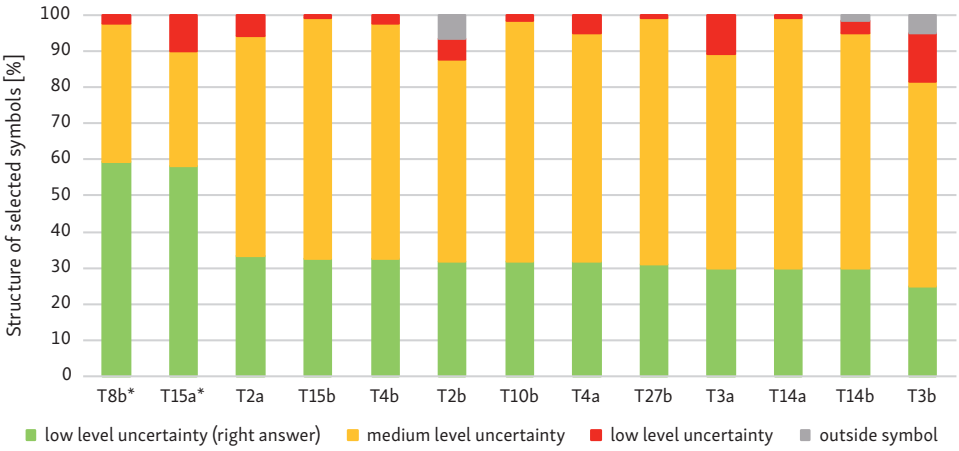


Fig. 6 – Structure of selected symbols by uncertainty level (the stimulus contained two symbols show certain data, the others only 1)

which reached 5.8% of the total number of representatives. A balanced result was achieved even in the comparison between the group of cartographers and laypersons. This symbol set could be suitable for wider usage.

Scanpath length was used to identify the difficulty or clarity of a given question (Fig. 7). The overall best result was recorded with the T10b set. This can be attributed to a rather distinctive graphical resolution of each level of uncertainty. The values of scanpath length are shown in Figure 6. In the second position was the T15b set and in third was the T8b. Scanpath length of the cartographers was

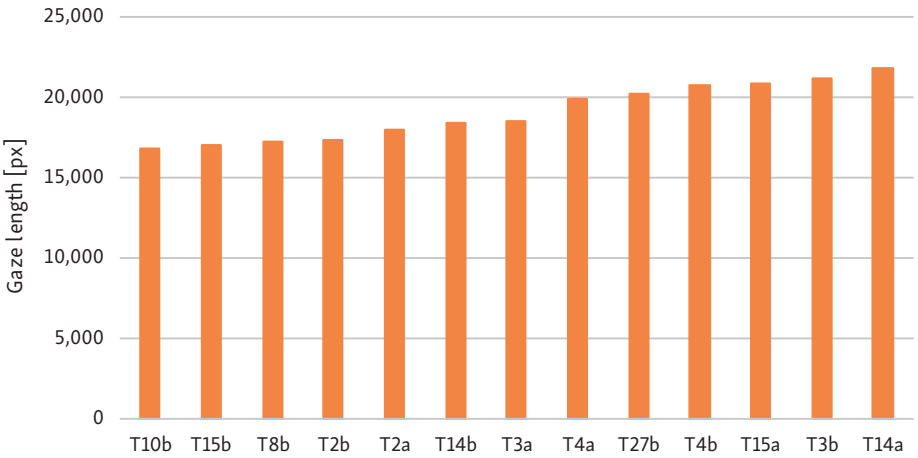


Fig. 7 – The scanpath length of the respondents' eye trajectory

Table 1 – The proportion of the total fixation time corresponding to individual parts of the map composition (gray tinted fields mean shorter fixation time)

	Total fixation time proportion (%)			
	Variant "a"		Variant "b"	
Comparative stimuli	Legend	Map field	Legend	Map field
T2	18.40	77.50	14.68	82.73
T3	18.70	77.14	18.04	78.63
T4	14.84	81.80	15.66	82.38
T14	20.16	75.39	14.46	82.76
T15	18.61	76.86	16.25	81.41

on average 2.2% longer, especially in the more complicated graphic design of the symbols, except the T3b, T14a, and T15b sets. A relatively significant difference is also evident in the placement of trials according to the chosen legend type. The first four places were occupied by the "b" variant of stimuli, which incorporates the level of uncertainty directly into the symbols of the phenomenon.

As mentioned above, we examined two types of symbols set legends (Fig. 3). Table 1 shows a list of the results of the compared trials incorporating different legend form. Each symbol set is assigned a value that corresponds to the proportion of the total fixation time spent in the legend area and the map field (Areas of Interest), always for the variants of legends "a" and "b" (Fig. 8). Thanks to this evaluation method, an objective result is achieved because the individual values determine the proportion of the total time on fixations of the given trial. This eliminates the effect of the various execution complexities that would occur when using absolute values such as fixation time. Based on the results, it is obvious that version "b" dominated, except for one case where a shorter fixation time in the legend area in favor of the map field was always found. Based on this, it can be concluded that this mode of sage was a more intuitive form of implementation. These results were compiled for all respondents, without a breakdown into groups by education. We examined the data and found only one significant difference between groups, and that was in the proportion of the fixation time found in the area of the legend, which was lower for laymen.

Due to the inconsistent result, it is not possible to determine the universally more appropriate implementation of the legend. It is always necessary to consider the plurality of phenomena which will be depicted in the map. In the case of one, it is more appropriate to choose variant "a". When more than one symbol is displayed, variant "b" is superior. Moreover in 2nd questionnaire the participants evaluated variant "b" as better perceived.

Sequences of the visited AOIs were imported into ScanGraph. For the analysis, the Levenshtein algorithm was used, and the parameter was set to 1.0 (similarity

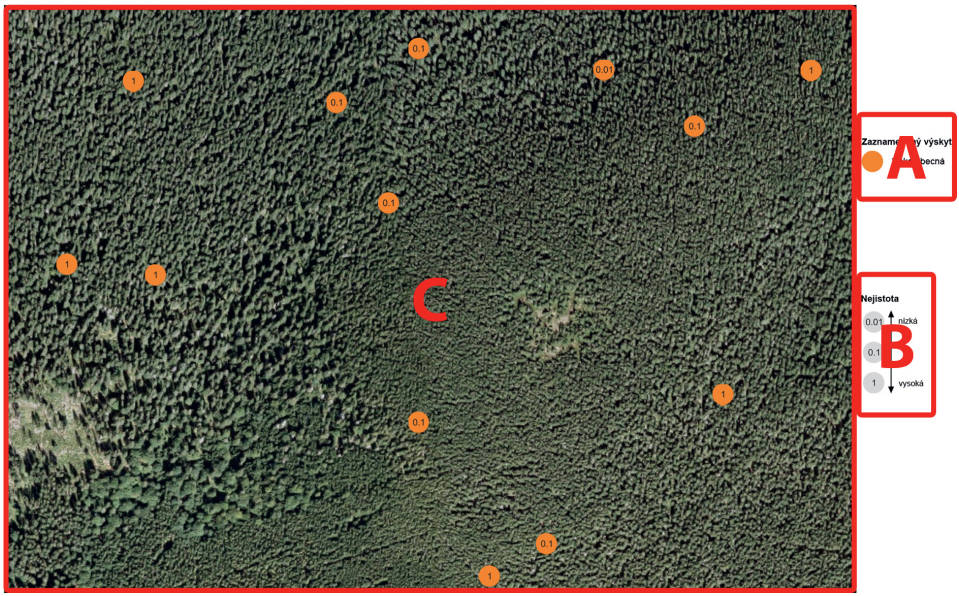


Fig. 8 – Places of interest marked on stimulus S2a

100%). That means that we were looking for participants with the same strategy of map reading. The important fact is that option "collapsed" was set, so there were no successive fixations in the sequences. For example, if a participant performed three fixations in each of the marked AOIs (AAABBBCCC), the sequence with the "collapsed" option will look like ABC. The tool's intended use is for finding similarities across different groups of participants (male/female; cartographer/non-cartographer). However, in this case, no such trend was found. So, it is not possible to say that for example, cartographers used a completely different strategy to non-cartographers. Figure 9 shows the groups' mixed nature (cartographers and non-cartographers). Cartographers are displayed as dark dots; non-cartographers are represented by bright dots.

For that reason, the tool was used in a slightly different way. Figure 10 is enhanced by the sequences that were recorded for found groups. It is evident that there is almost no "A" letter in these sequences. All sequences started with the letter "C" which means that the respondents investigated the map. It is logical because their gaze started from the center of the stimuli. In few cases, fixation in AOI "A" follows. However, respondents looked there only once, and no other fixation on this AOI is recorded.

This corresponds to the average number of fixations, which is 69 in the map (C), 16.5 in the part describing the uncertainty (B) and only 4 fixations in the first part of the legend (A).

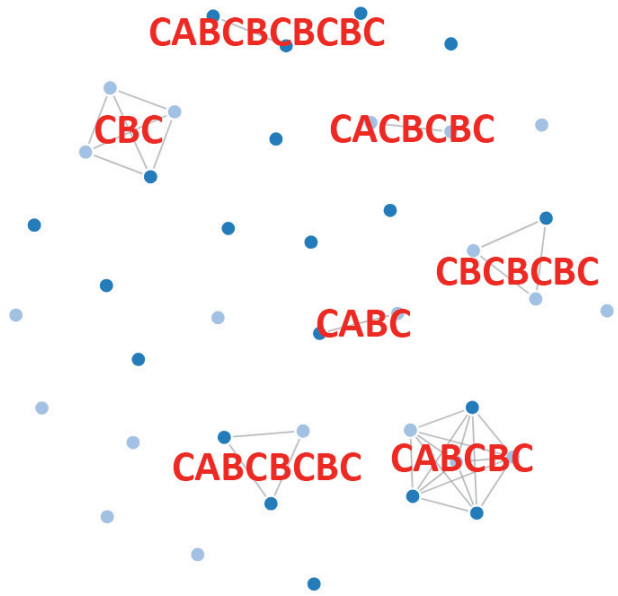


Fig. 9 – Groups of participants with the same sequence of visited AOIs on the example of stimulus 2A

In the next step, data for all five pairs of stimuli were combined, and similarity of the visual inspection strategy was analyzed across all stimuli. The graph now contains 200 nodes (40 participants × 5 stimuli) and their color does not represent if they are cartographers, but the belonging to the stimulus. Similar behavior as for the stimulus 2a was observed for all stimuli (with "a" variant of the legend). If the fixation in AOI "A" was recorded, it is only once at the beginning of the sequence.

The graph in Figure 11 depicts the average number of fixations recorded in the two legend AOIs. In the case of variant A – the total value was given as a sum of fixations in part A (grey) and part B (yellow).

4.2. The overall ranking of the symbol set

The final scoring of the tested symbol was based on ranking within the parameters gained by eye-tracking metrics and the second questionnaire which was held after the eye-tracking trials. Participants of experiment evaluated the user preferences of symbols via the 2nd questionnaire This evaluation was beneficial for T4b and T8b symbol sets (Table 2). These symbol sets achieved the same result with a median of the overall score of 6. This was followed by sets T15b and T10b, which also achieved a median of 6, but their scores included significantly lower marks of

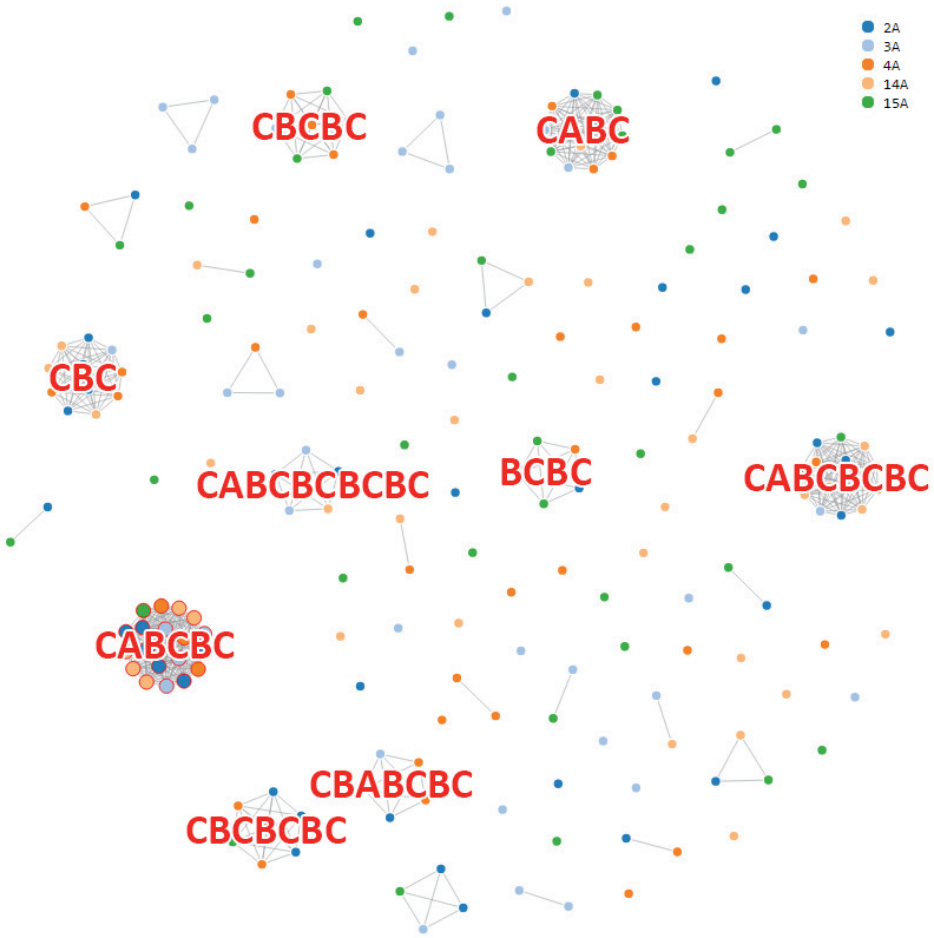


Fig. 10 – Groups of participants with the same sequence of visited AOIs across five stimuli with the "a" variant of the legend

perceived suitability, thus placing them in 3rd and 4th place. In a comparison of preferences of legend type, the first 6 places were occupied by the implementation of B legend variant. It can be said that users prefer this implementation and it can be recommended as a more suitable variant based on individual sub evaluations.

Table 2 contains the order of symbol sets within each evaluated criterion. The best result was achieved by the T8b, T10b and T15b sets. Again, it is necessary to draw attention to the possible distortion of the result for the T8b and T15a sets. In case of evaluating individual symbol sets by combining the results of both trials containing them and differing only in the chosen legend variant, then the best result would be achieved by the T2a/T2b pair. Results proved that users prefer

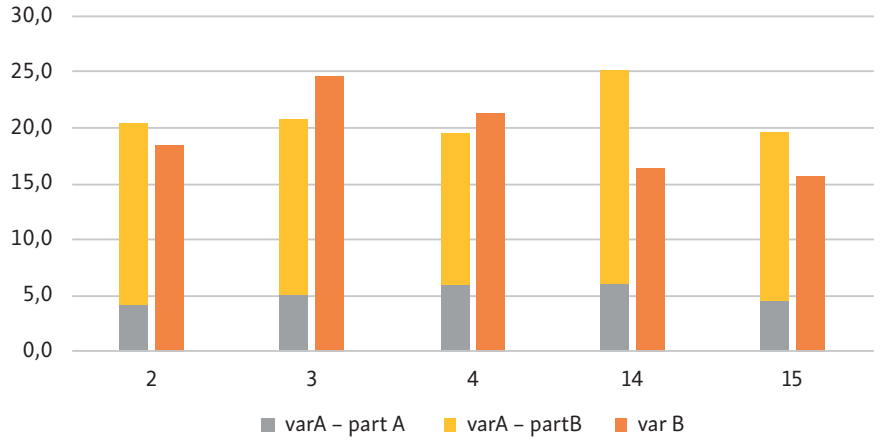


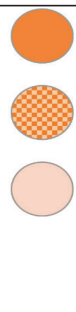
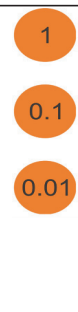
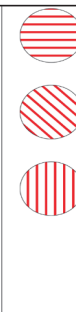
Fig. 11 – Average number of fixations in legend AOI

and intuitively work with symbols using saturation as information about the uncertainty. Interestingly, the same symbol set T15b and T15a work differently when using different legends. There are also differences between respondents' rankings of suitability and the overall performance of symbols in the eye-tracking task. The demonstrative example is T4b, which was chosen as most suitable, but during testing was in the middle of ranking.

5. Conclusion and discussion

During the experiment, we validate several theories. Simple user preference of symbols doesn't equate to their suitability for practical development. As an example, consider set T14b, which used fuzzification. Majority of respondents favored this symbol set and its modifications. Subsequently, they did not perform well during the eye-tracking task and were also ranked lower in the second questionnaire, mainly to the difficulty they presented in actual use. This finding is in contrast to the work of MacEachren et al. (2012) where fuzziness works particularly well. In this study the authors also do not recommend saturation. In our experiment, this symbol set was the best ranked. The main difference between the studies is with the parameters for ranking the symbols. The ranking parameters were the number of correct answers to the given question, the average trial tracking time, the average length of the eye trajectory, and the level of perceived suitability. We can also prove that there is a clear difference in intuitiveness for representing uncertainty among symbols based upon individual visual variables. In contrast to MacEachren et al., we considered the way the legend was implemented. The results showed

Table 2 – Final ranking of symbol sets

Symbol set	 T8b	 T15b	 T10b	 T2a	 T2b	 T4b	T14b	 T15a	 T3a	 T4a	 T14a	 T27b	 T3b
Correctness of question	1	4	7	3	6	5	12	2	10	8	11	9	13
Trial duration	1	4	3	7	8	12	6	5	2	9	10	13	11
Gaze length	3	2	1	5	4	10	6	11	7	8	13	9	12
Evaluation of suitability	2	3	4	8	6	1	5	11	12	7	10	13	9
Final ranking	1	2, 3		4	5	6	7, 8		9	10	11, 12		13

that symbols which directly incorporate uncertainty in the visual variable work better than legends with separation of uncertainty and symbols. This is mainly because its appearance can significantly affect the speed and accuracy of the interpretation of the results. Even more in all parts of the work, the results were compared between groups of respondents with and without GIScience education. This step aimed to evaluate the impact of this knowledge on the process of reading a map with a representation of uncertainty. The cartographers represent an expert opinion, and a group of laymen then provides a way of understanding how people without GIScience background get the information from the map. Thanks to this knowledge, it is possible to design symbol sets in such a way that their practicability can target a wider audience. In fact, our results suggest that with reference to the particular symbol sets we examined, those with GIScience background and laypersons utilize each legend type similarly. More research in different map environments can build on these initial findings.

Additionally, the experimental setup can be biased by several in-text mentioned problems. A continuing area of concern is in the understanding of the term 'uncertainty', even in the GIScience community. It remains relatively unusual to find users with knowledge about spatial data uncertainty. Due to this general naivety to the term 'uncertainty', we were concerned that the results could be affected if we were show examples to participants at the start of the eye-tracking study. For this reason, we provide an explanation but not show visual form of uncertainty visualization before the experiment, in order to prevent possible bias.

Nonetheless, we believe that the presented study will aid in the understanding of user preferences and to show a possible direction of research to assess user preferences through quantitative methods.

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The content of this Special Issue of Geografie Journal has been prepared together with the International Cartographic Association, namely with the Commission on Cognitive Issues in Geographic Information Visualization, the Commission on Use, User and Usability Issues, and the Commission on Atlases. Selected authors were contacted during the ICA Commissions' joint workshop "Atlases, Cognition, Usability" held in Olomouc (Czechia) at Palacký University in April 2018. The content of the Special Issue reflects the current topics handled by the Commissions and we hope that the special issue increases awareness and knowledge of cognitive and usability issues with geographic information among the broader geographic community. Preliminary selection of manuscripts and pre-submission communication with authors was done by Petr Kubíček (Masaryk University, proposed incoming co-Chair of the Cognitive Issues in Geographic Information Visualization Commission) and Amy Griffin (RMIT University, current co-chair of the Cognitive Issues in Geographic Information Visualization Commission). We thank all of the authors who contributed their research to this special issue.

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APPENDIX 7

Comparison of apiculture and winter mortality of honey bee colonies (Apis mellifera) in Austria and Czechia

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Comparison of apiculture and winter mortality of honey bee colonies (*Apis mellifera*) in Austria and Czechia

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ABSTRACT

Honey bees are the most important managed pollinators and provide income because of bee products. In Austria and Czechia, we monitored winter losses of honey bee colonies and also collected information on the apicultural sector, hive management, population dynamics and treatment against the mite *Varroa destructor* from 2013–14 to 2016–17. Numbers of beekeepers and colonies, colony density and percentage of beekeepers in human population are higher in Czechia than in Austria. Winter loss rates of honey bee colonies ranged from 8.1% to 28.4% in Austria and 6.4% to 19.4% in Czechia, with significantly higher loss rates in all 4 investigated winters in Austria. The portion of colonies lost because of living colonies with unsolvable queen problems ranged from 3.6 to 4.4% in Austria and from 2.2 to 3.0% in Czechia. Despite of colony losses during winter, colony production in summer allows for compensation or even expansion of colony populations in both countries. We identified differences between the two countries in the treatments applied by beekeepers against the parasitic varroa mite. In Austria, organic acids are most commonly used, whereas the application of synthetic acaricides is widely spread in Czechia. Our study points at the better understanding of apiculture and the importance of international comparisons to facilitate our knowledge on honey bee colony losses.

1. Introduction

Honey bees are the most important managed pollinators of wild plants and agricultural crops. The total economic value of pollinators was estimated to represent 9.5% of the value of the world agricultural production used for human food (Gallai et al., 2009). Despite wild insect pollinators have higher pollination impact on crops (Garibaldi et al., 2013), honey bees are still the most important managed pollinators of wild plants and agricultural crops. Given the importance of managed honey bee colonies for economy and ecology, colony losses have been in the focus of research in the last years. Honey bee colony failure may occur at any time of the year, but in temperate climate, winter is a drastic challenge for colonies. Forage is not available, brood production is ceased and workers need to survive several months instead of a few weeks in summer. One of the main information sources on winter colony losses is voluntary crowd sourcing data from internationally standardized questionnaire studies. In many countries, data collection is coordinated by the international association COLOSS (Prevention of honey bee COlony LOSSes, Neumann and Carreck, 2010; van der Zee et al., 2013). Loss rates presented by COLOSS fluctuated from very high winter losses to winters with moderate or low mortality rates (Brodschneider et al., 2016, 2018; van der Zee et al., 2012, 2014). A similar trend was reported from United States beekeepers (van Engelsdorp et al., 2010; Lee et al., 2015a; Kulhanek et al., 2017).

Austria and Czechia have historically shared beekeeping thanks to geographical as well as cultural proximity. Some historically important persons related to beekeeping, e.g. Franz Hruschka, the inventor of the honey extractor or Gregor Johann Mendel, beekeeper and father of genetics, have their cultural background in the common history of both countries. Empress Maria Theresia founded the first beekeeping school in Vienna in 1769 and induced other activities for prosperity of apiculture (Pechhacker and Moosbeckhofer, 2003). She influenced the beekeeping of Austria and Czechia until today by her 1775 document on the freedom and prosperity of apiculture (Schulz, 1991). Both countries breed mainly *Apis mellifera carnica* bees in last decades (Brascamp et al., 2016). Today, a vast majority of beekeepers in the two countries are hobby, or backyard, beekeepers with a small number of hives. Beekeeping practice of backyard beekeepers might be different compared to large beekeeping operations, which could affect honey bee colony winter loss rate. This effect was demonstrated in multi-country comparisons of winter colony losses (Brodschneider et al., 2016, 2018). In both countries, beekeepers

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are organized in local and national beekeeping clubs. Official information about number of beekeepers and their colonies are collected by beekeeping organizations or administrative authorities, e.g. ministeries. Registration as a beekeeper, including the number of maintained colonies and apiary location, is mandatory in Czechia for many years, but has only started recently in Austria.

The aim of this publication is to compare apiculture in Austria and Czechia. We therefore collected key numbers that describe beekeeping in both countries. We analysed data which were collected by citizen scientist beekeepers between 2014 and 2017 using the COLOSS questionnaire. Such data has previously been used to identify regions with high loss rates and to identify risk factors, for example due to parasites, diseases or environmental factors (van der Zee et al., 2012, 2014, 2015; Simon-Delso et al., 2014; Switanek et al., 2017; Kuchling et al., 2018). Although winter loss rates of honey bee colonies in the two countries of single years have been published previously (Brodschneider et al., 2010, 2016, 2018) we here present a comprehensive summary of winter losses since 2013-14 to 2016-17 and accompanying information. In this study, we emphasize honey bee winter losses due to queen problems. Genetics, health and fitness of honey bee queens have been identified as important factors for overall colony health and winter colony losses, nevertheless the occurrence of this problem has rarely been investigated on a large scale (Genersch et al., 2010; van Engelsdorp et al., 2013; Smart et al., 2016). Our aim is therefore to clarify, if queen problems remain at a constant level or increase when high colony loss rates are recorded. We were also interested if there is a difference in the frequency of queen related problems between the two different countries. Based on winter loss rates and net changes of colony numbers during summer, we have modelled the changes of honey bee population in Austria and Czechia. Finally, we investigated different treatment strategies of beekeepers against the ectoparasitic mite *Varroa destructor* (Rosenkranz et al., 2010) in Austria and Czechia.

2. Material and methods

2.1. Comparison of apiculture in Austria and Czechia

To compare the apicultural sector between Austria and Czechia, official information from beekeeping organizations (Biene Österreich in Austria) or ministeries (Ministry of Agriculture of the Czech Republic) on numbers of beekeepers and honey bee colonies was used. From these data, calculations of average operation size, colony density, colonies per capita, percentage of beekeepers in population, change in number of beekeepers and colonies between 2013 and 2016 and response rate in winter loss survey were made. Calculations based on country area or population were made using the EUROSTAT dataset (EUROSTAT, 2018).

2.2. Honey bee colony winter loss rate

The winter loss rate was surveyed using the standardized COLOSS questionnaire in Austria and Czechia each spring between 2014 and 2017 (van der Zee et al., 2013). Participation was based on voluntary basis and anonymous responses were possible. In both countries, the survey was promoted by beekeeping journals, internet and during beekeepers meetings. Data were collected mostly online but also in paper form to reach all interested beekeepers from all regions. Multiple entries, incomplete or illogic datasets were removed prior the data analysis. The winter loss rate and 95% confidence intervals were calculated according to van der Zee et al. (2013). Since 2014/15, beekeepers were asked also to differentiate their losses between colonies that were dead or reduced to a few hundred workers (empty hives) and colonies that were alive but had unsolvable queen problems (like a missing queen, laying workers, or a drone-egg laying queen). Both categories were used for separate loss rate calculation, but summed up for overall loss rate. In 2017, beekeepers additionally could submit counting of colonies lost by natural disaster during winter 2016/17. These colonies were not included in overall loss rate calculation as they are the result of occasional events, rather than disease or other epidemiologic relevant causes of colony losses.

We calculated the relative frequencies of operational loss (i.e. the loss rate experienced by individual beekeeping operations) divided into 5 categories. These categories were no operational losses (0%), losses between > 0 and 10%, > 10 and 30%, > 30 and 50% and more than 50% of the wintered honey bee colonies (Brodschneider et al., 2010).

2.3. Biannual honey bee colony population dynamic

From 2014 to 2017 we asked beekeepers in Austria and Czechia on the number of colonies in previous spring and previous autumn using standard mandatory questions from the COLOSS questionnaire. The number of colonies in spring of the actual survey year was derived by subtracting the number of colonies lost during winter from the number of colonies managed in autumn. From this we calculated the total colony stock numbers of all participants providing all necessary numbers. Then we calculated ‚summer change rate', ‚winter loss rate', ‚spring-spring change 'and ‚spring autumn estimation 'of this subsample of beekeeping operations according to Fig. 1. Here we defined ‚winter loss rate 'as the sum of dead colonies and the colonies with queen problems for the first three years. For 2016-17, the wording of the questionnaire was slightly changed, hence also the colonies lost due to natural disaster were included in this analysis (Brodschneider et al., 2018). ‚Summer change 'is the net change in number of colonies from spring to autumn, mostly comprised of own breeding or purchase of colonies. Summer change could also include colonies lost, merged or sold colonies. ‚Spring-spring change 'compares the colony numbers in spring of two consecutive years. ‚Spring-autumn estimation 'calculates the rate of colony production needed to re-establish the number of colonies before winter (previous autumn). The latter is therefore only affected by the winter loss rate and not by any other measured parameter. After calculating all these change rates for each country, we applied these change rates to 100 fictitious honey bee colonies for Austria and Czechia, respectively, to model the theoretical development of honey bee populations based exclusively on these change rates.

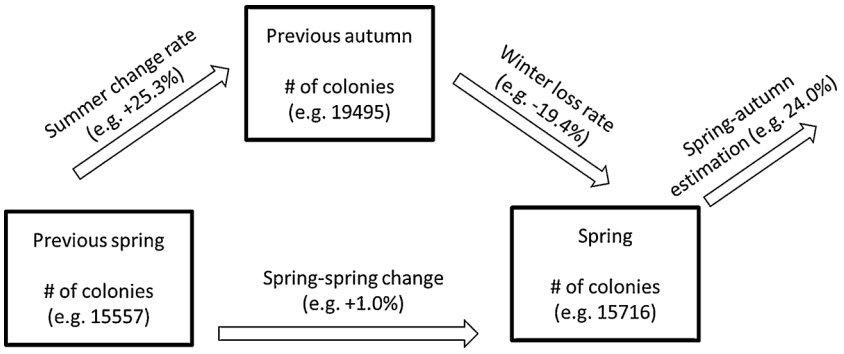


Fig. 1. Scheme of terminology and dates of colony numbers as collected using the COLOSS questionnaire in Austria and Czechia 2014–2017 (in boxes) and terminology and parameters calculated from the colony numbers in ‚previous spring', ‚previous autumn 'and ‚spring'. Calculated parameters of colony population change are shown as arrows (‚summer change rate', ‚spring-spring change', ‚winter loss rate 'and ‚spring autumn estimation'). Spring autumn estimation is the increase needed to re-establish the previous autumn population based on the number of surviving colonies in spring. To further illustrate calculations, examplary data of 2014-15 from 959 Czech beekeeping operations is shown.

Table 1
Comparison of the apicultural sector in Austria and Czechia.

	Austria[a]	Czechia[b]
Number of beekeepers (2016)	26609	58581
Number of honey bee colonies (2016)	354080	693069
Average operation size (number of colonies)	13.3	11.5
Honey bee colony density per square km	4.2	8.8
Honey bee colonies per capita	0.04	0.06
Change in number of beekeepers between 2013 and 2016	+4%	+13%
Change in number of colonies between 2013 and 2016	−8%	+40%
Percentage of beekeepers in population	0.3%	0.6%
Response rate in winter loss survey (percentage of beekeeping operations, 2014-2017)	4.0%, 5.0%, 4.9%, 6.2%	1.1%, 1.7%, 1.7%, 2.0%

[a] Data and calculations based on annual reports from Biene Österreich.
[b] Ministry of Agriculture of the Czech Republic.

2.4. Treatment against Varroa destructor

In all four years the questionnaire contained the same question on the months when beekeepers started a treatment or management plan against *V. destructor* during the period April of the previous year to April of the respective year. The table in the questionnaire contained a number of different treatments, irrespectively the treatment is recommended or authorised in the two countries.

3. Results

3.1. Structure of apiculture in Austria and Czechia

The comparison of some key characteristics of Austrian and Czech apiculture is summarized in Table 1. Number of beekeepers, honey bee colonies, colony density and percentage of beekeepers in human population are higher in Czechia than in Austria. Average operation size is comparable between the two countries. Based on the official datasets, we calculated the change in number of beekeepers and colonies for the study period. We found that number of beekeepers increased in both countries (Table 1). Colony numbers increased in Czechia, whereas there was a slight decrease in Austria.

3.2. Winter losses of honey bee colonies

In both countries, participation in the surveys increased during the four years of investigation presented here. Altogether we collected 5227 answers from beekeepers wintering 108,946 colonies in Austria, and from 3688 beekeepers collectively managing 72,225 colonies in Czechia. Sample sizes (number of participating beekeeping operations) for individual years and winter honey bee colony loss rates are shown in Fig. 2. For comparability, Fig. 2 includes older data from the Austrian study on winter loss rates that have partially been published before (Brodschneider et al., 2010; van der Zee et al., 2012, 2014; Brodschneider and Crailsheim, 2013). Our study represents between 4.0 and 6.2% of Austrian beekeeping operations and 1.1 and 2.0% in Czechia (Table 1). Beekeepers from all regions of Austria and Czechia participated in our study, as shown in Fig. 3. There were no significant differences in response rates among different districts in Czechia (data not shown).

We found that in both countries the winter loss rate was fluctuating from year to year, whereas beekeepers in Czechia always experienced significantly lower losses compared to Austria (which can be seen by non-overlapping 95% confidence intervals in Fig. 2). The highest loss rates were recorded for the winter of 2014-15, where 28.4% of honey bee colonies in Austria and 19.4% of colonies in Czechia did not survive winter. The lowest loss rates were found for the following winter 2015-16, where in Austria 8.1% and in Czechia 6.4% of colonies did not survive winter. Winter losses in Austria and Czechia also varied among regions of the two countries, Fig. 4 depicts

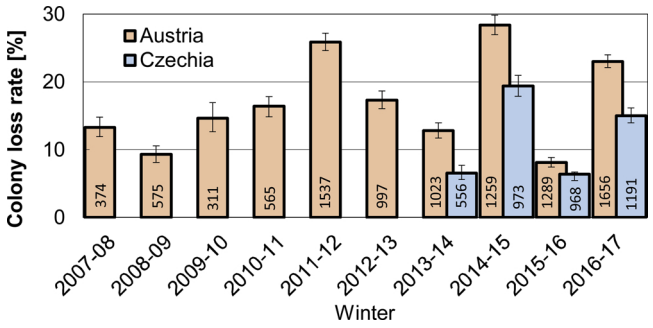


Fig. 2. Winter loss rate (and 95% confidence interval) of honey bee colonies in Austria (red) and Czechia (blue) for the last ten and four years, respectively. Sample size = number of beekeeping operations.

regional loss rates of the four investigated years. We found that the majority of beekeeping operations in both countries experienced no or low losses (Table 2). Substantial losses of more than 50% of the colonies were experienced by less than a quarter of all beekeeping operations, and particularly happened in the two winters with higher loss rates (2014–15 and 2016–17).

Queen problems marginally contributed to winter colony losses in both countries. The extent varied between 3.6 and 4.4% in Austria and from 2.2 to 3.0% in Czechia (Fig. 5). Losses caused by queen problems are relatively stable in both countries among surveyed years, whereas the losses due to dead colonies or empty hives fluctuated greatly in both countries.

3.3. Biannual honey bee colony population dynamics

The loss rates presented in Table 3 slightly differ from the loss rates in Fig. 2, because only the subsample of beekeepers that completely submitted all relevant information for calculation of population dynamics (Fig. 1) were used (compare sample sizes in Table 3 and Fig. 2). Colony population numbers for the dates, previous spring‘, ‚previous autumn ‘and ‚spring ‘of years 2014 to 2017 are presented in Table 3. Summer change rate was between +24.4 and +44.9% in Austria and +15.2 and +27.2% in Czechia. These exceed our calculated ‚spring-autumn estimation ‘which is needed to re-establish the previous autumns colony population (see Table 3, compare ‚spring autumn estimation ‘with ‚summer change rate ‘of next year). ‚Spring-spring change ‘of colony numbers has been negative in only one year in Austria (2014–15) and Czechia (2016–17), respectively. This underlines that the number of colonies maintained the previous spring was reached or even overrun in most of the years.

Based on the change rates shown in Table 3, we modelled the development of 100 fictitious honey bee colonies each in Austria and Czechia, respectively. Fig. 6 shows the decrease of colony numbers during winter, which is always followed by an increase during summer. After four years, the models suggests a possible net increase of 52 colonies in Austria and of 36 colonies in Czechia based on ‚winter loss ‘and ‚summer change ‘rates.

3.4. Varroa fighting strategies in Austria and Czechia

Approximately three quarters of Austrian and Czech beekeepers monitor the mite infestation level of their colonies (Fig. 7). The exact monitoring methods were not recorded in the questionnaire. The biotechnological treatment method ‘drone brood removal’ was performed by 63% of Austrian beekeepers, but only by 36% of Czech beekeepers, respectively. Among the medicaments to fight Varroa, treatments based on organic compounds are preferred by beekeepers in Austria. Czech beekeepers rather apply synthetic treatment strategies. Short term formic acid (52%) and long term formic acid (46%) evaporation, followed by oxalic acid sublimation (42%) and oxalic acid trickling (28%) are the most commonly applied treatments in Austria. On the other hand, Czech beekeepers mainly fumigate colonies with amitraz (84%) or apply short term evaporation of formic acid (60%). Gabon strips are inserted into colonies by 33% of Czech beekeepers and 20% apply long term evaporation of

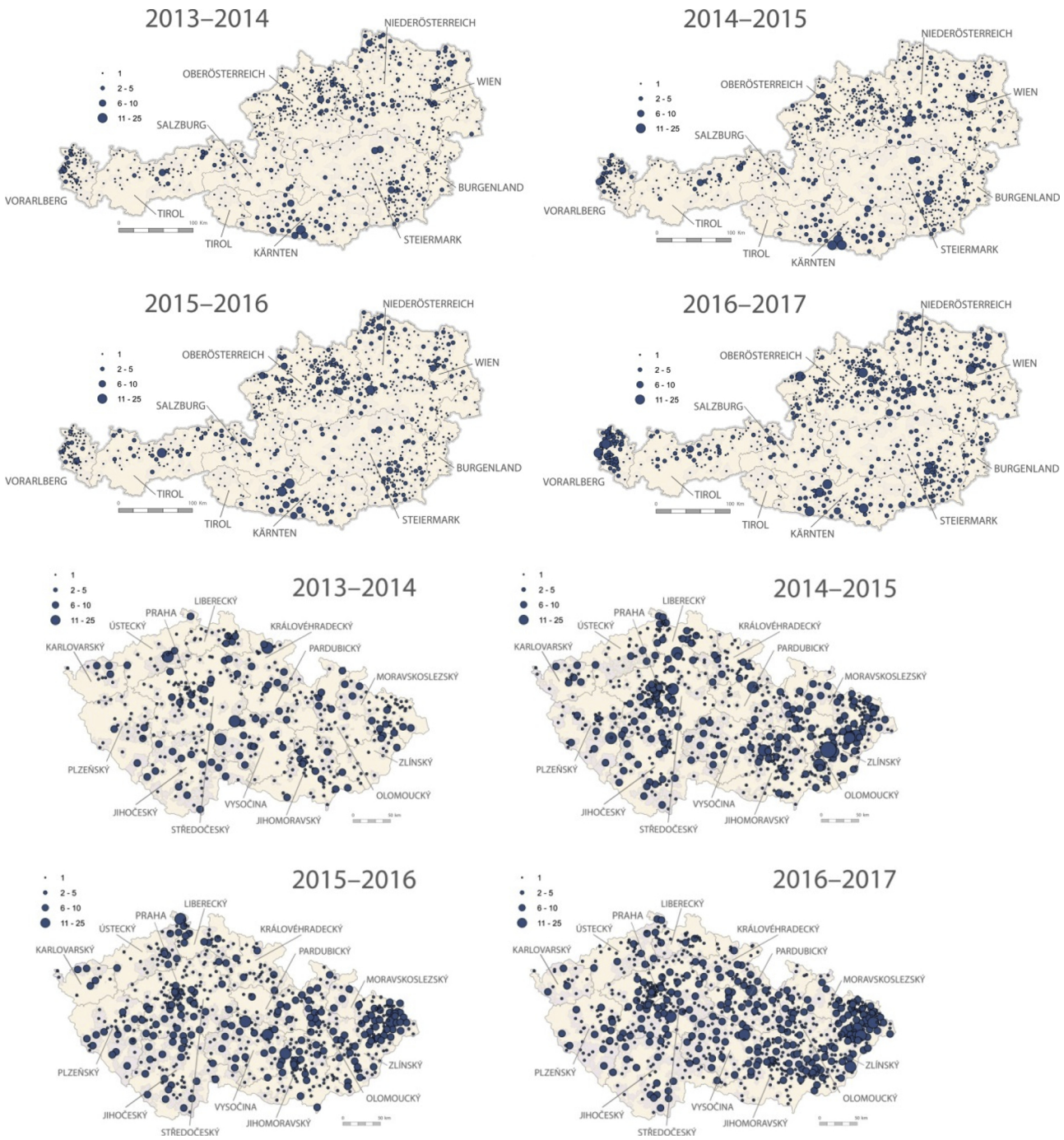


Fig. 3. Geographic origin and number of beekeeping operations participating in Austria and Czechia during the four studied years. Respondents from Vienna are excluded.

formic acid. Only a limited number of Czech beekeepers use hyperthermia compared to Austria (1 and 5%, respectively). Products like Bienenwohl/Beevital-Hiveclean were used only in Austria because they were not registered in Czechia at the time of the study. The opposite situation is for tau-fluvanilate and amitraz, which are not applied in Austria. Beevital-Hiveclean has been renamed to VarroMed in all EU countries since 2017.

4. Discussion

4.1. The structure of apiculture in Austria and Czechia

Apiculture in agricultural context is often characterized by key numbers that allow international comparisons (Daberkow et al., 2009; De la Rúa et al., 2009; Chauzat et al., 2013). In this study we present the probably most detailed comparison of the apiculture of two countries. Austria and Czechia are two neighboring European countries of similar size and common history, but have different development of beekeeping in the last 100 years. Our study, for example, underlines that there is more than the double number of honey bee colonies managed in Czechia, compared to Austria. In both countries, operation size is rather small (Table 1) compared to other countries (Chauzat et al., 2013; Lee et al., 2015a), with the majority of beekeeping operations being hobbyist or sideline beekeepers (Brodschneider et al., 2010). One could base this difference in colony numbers and colony density between the two countries to different landscape composition in the two countries, but except for the larger areas of mountainous regions in

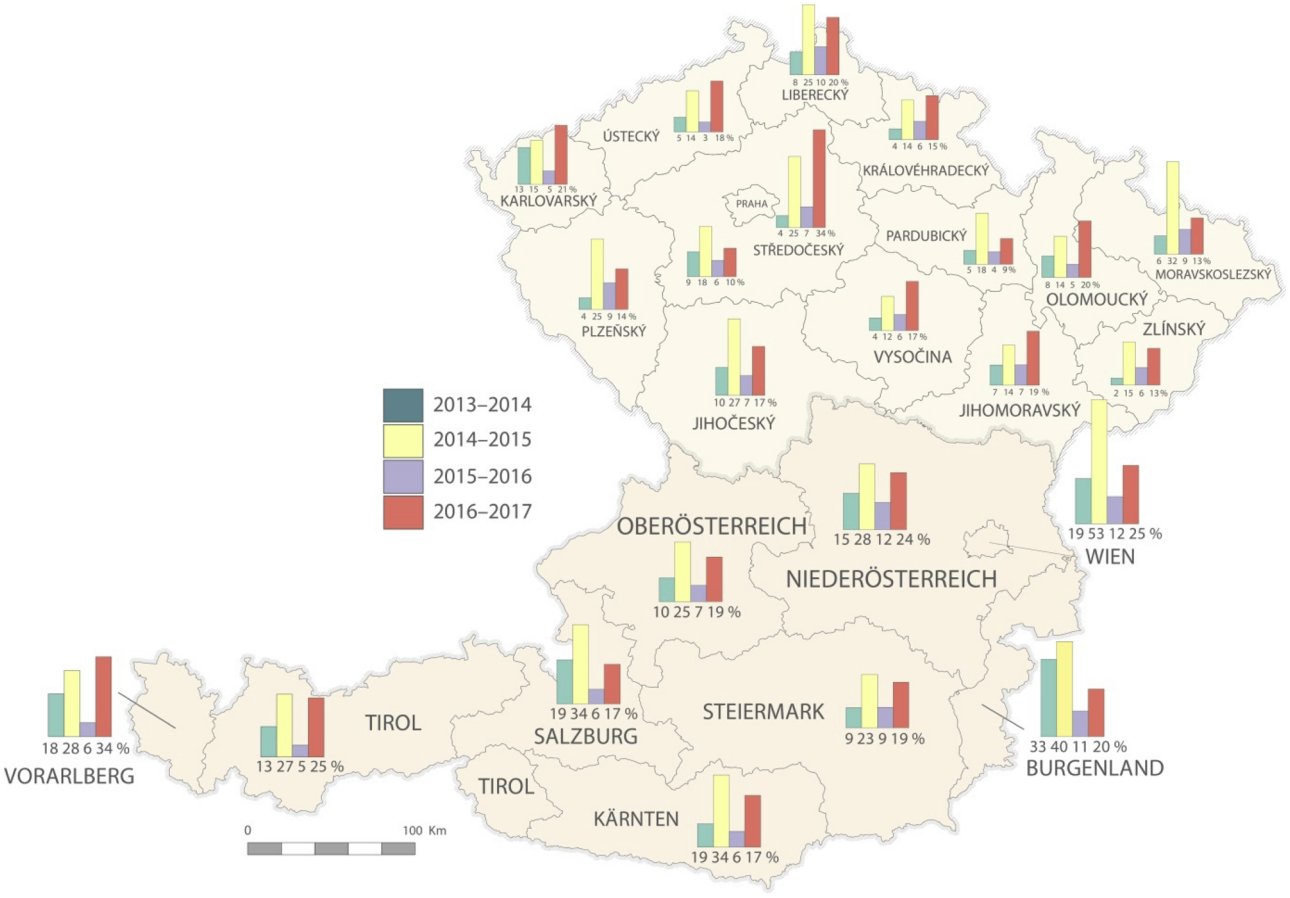


Fig. 4. Honey bee colony losses (sum of dead colonies and colonies lost due to queen problems) for the winters 2013–14 to 2016–17 in Austrian and Czech regions. Total sample size per year is the same as in Fig. 2.

Austria, the landscape structure, in particular the cultivation of agricultural crops (data not shown), is quite similar. Our analysis rather suggests that this gap in number of bee colonies and colony density can be attributed to the higher interest in beekeeping in Czechia. We illustrate this higher interest in beekeeping by the higher number of beekeepers related to the total population and the higher number of hives per capita in Czechia, compared to Austria (Table 1). For Czechia, a comparison with older literature suggests that the proportion of beekeepers in the population has not much changed, as Pokorný (1928) similarly to our findings reported about six beekeepers per 1000 capita. The strong connection between human management for hobby or income underlines the importance to enthuse and reward people for beekeeping to maintain stable honey bee populations (Vural and Karaman, 2009; vanEngelsdorp and Meixner, 2010; Simpach, 2012; Brodschneider and Crailsheim, 2013). Therefore, the socio-economics of beekeeping as a source for income need to be strongly considered for sustainable honey bee populations (Sumner and Boriss, 2006). A survey performed in UK found that a household would pay around 43 £ yearly for protection policy (Mwebaze et al., 2018).

4.2. Losses of honey bee colonies

The major problem in beekeeping seems to be colony losses (van Engelsdorp et al., 2010; Brodschneider et al., 2016; Kulhanek et al., 2017). In this study we summarize the existing winter mortality data of Austria and Czechia (Fig. 2). In the four years we present comparable data from both countries, Czechia always experienced lower losses than Austria, although the trends for high or low losses are the same in both countries. We need to point out that these results are based on subsamples of beekeepers, and hence honey bee populations. The response rate of our survey was higher in Austria (between 4.0 and 6.2% of beekeeping operations) than in Czechia (1.1 to 2.0%, Table 1). The difference in loss rates between the countries could therefore also be affected by slight differences in the beekeeper population surveyed (van

Table 2
Percentage of beekeeping operations with no operational losses (0%) or that experienced winter losses between > 0 and 10%, > 10 and 30%, > 30 and 50% and more than 50% of their wintered honey bee colonies. Data is from four winters in Austria and Czechia, sample size is the same as in Fig. 2.

Operational loss	Austria				Czechia			
	2013-14	2014-15	2015-16	2016-17	2013-14	2014-15	2015-16	2016-17
0%	40.0%	19.9%	49.0%	26.3%	58.6%	38.7%	62.4%	41.9%
> 0% - 10%	19.3%	10.7%	19.9%	12.3%	20.7%	16.4%	17.8%	18.6%
> 10% - 30%	24.6%	26.2%	20.4%	28.5%	15.3%	20.2%	15.3%	24.0%
> 30% - 50%	8.8%	19.8%	6.1%	15.0%	3.2%	10.9%	3.1%	9.0%
> 50% - 100%	7.3%	23.4%	4.7%	17.8%	2.2%	13.7%	1.4%	6.5%

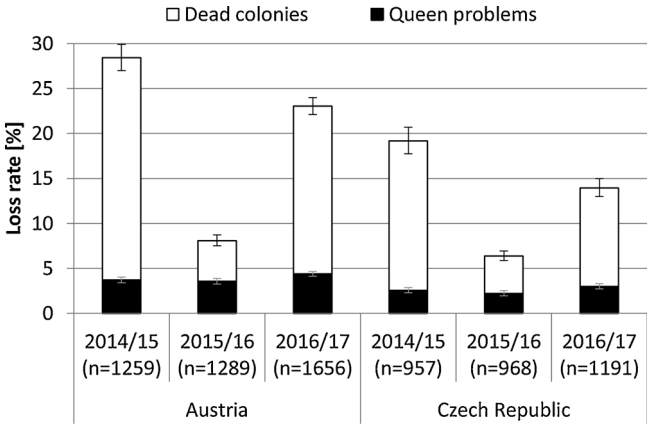


Fig. 5. Percentage of colonies lost during winter in Austria and Czechia due to dead colonies (many dead bees or empty hives) and due to queen problems (a missing queen, laying workers, or a drone egg laying queen). The 95% confidence intervals for both, queen problems and dead colonies are shown (n = sample size of number of beekeeping operations).

der Zee et al., 2013). Our results show large variations in winter colony loss rates between regions in both countries (Fig. 4) and also among the beekeeper community. Table 2 shows the latter bias of losses, which severely affect only a small portion of beekeeping operations. This distribution of operational losses seems to be a general pattern and has been demonstrated before for Austria (Brodschneider et al., 2010) and Germany (Genersch et al., 2010).

Previous studies identified different factors of hive management to contribute to honey bee colony winter losses. For example, operation size, age of queens, disease control (treatment against mites), landscape composition and beekeeper education are believed to influence colony mortality (van der Zee et al., 2012, 2014; Brodschneider et al., 2016; Jacques et al., 2017; Kulhanek et al., 2017; Kuchling et al., 2018). The fluctuations we report here among years and regions are next to these factors probably depending on factors other than hive management. Albeit the general lower losses in Czechia, both countries experienced similar trends in high or low winter loss rates. Next to variations in amount and quality of forage available or disease and parasite pressures, weather could be a factor partially explaining such year to year variations (Simon-Delso et al., 2014; Switanek et al., 2017).

One special case of winter losses is caused by queen problems. Queen vitality is crucial for colony health and survival (Genersch et al., 2010; van Engelsdorp and Meixner, 2010; van der Zee et al., 2012, 2014; vanEngelsdorp et al., 2013v; Smart et al., 2016; Amiri et al., 2017). Honey bee colonies rely on a healthy and mated queen, which lives several years, greatly exceeding lifespan of workers (Corona et al., 2005; Brodschneider et al., 2012; Pettis et al., 2016). Colonies with eggs or young brood are able to rear emergency queens, in case of a queen running out of sperm stores, decreasing pheromone production, queen death or accident (Châline et al., 2003; Moritz et al., 2005; Sagili et al., 2018). However, in countries with a temperate or cold climate, no queen rearing is possible during winter and no drones will be available for mating with queens after winter. Beekeepers therefore may add surviving workers to other colonies, but colonies with queen problems after winter are regarded as lost colonies (van der Zee et al., 2013).

We found that queen problems account for a rather low and remarkably constant amount of winter losses, suggesting a baseline mortality of honey bee colonies during winter based on queen problems. The rate of queen problems during winter found in this study is lower than reports from the United States (Smart et al., 2016). Pettis et al. (2016) attribute colony failure to low sperm viability due to poor shipping conditions of queens, whereas in the by far smaller countries of our investigation, the majority of queens is typically bred and traded locally. It is important to point out that no trends in rise or decline of queen problems were found during the three years we studied this topic in Austria and Czechia. One limitation in the assessment of overwinter success and the assignment to simple symptoms of colony failure is caused by an often considerable time gap between the occurrence of an event, and the assessment by the (citizen science) beekeeper or apiary inspector. Also, our analysis on national level, without exceptional high queen problem rates, does not exclude local areas where elevated queen problems may exist, or certain factors, as shipping or pesticide exposure, harm queen quality (Williams et al., 2015; Pettis et al., 2016). The isolated view on queen problems during overwintering as described in this study can be approximately equalized to a natural winter loss rate in an almost ideal environment for the honey bee, without any external stressors. The established drivers that influence winter survival of the superorganism include exposure to pests and pathogens, pesticides or danger of starvation (Döke et al., 2015; Goulson et al., 2015). Even without these biotic or abiotic factors, queen problems will remain a biological relevant factor for colony survival, as there is a biological limit for honey bee queens' survival and functionality. Still, the queen loss rates presented here must be interpreted with caution as they are influenced by supersedure and beekeeping management, in particular *Varroa* fighting strategies with varroacides (Pettis et al., 1991; Rosenkranz et al., 2010; Giacobino et al., 2015).

4.3. Biannual honey bee population dynamics

Our model of honey bee populations displays regular fluctuations in colony numbers. Winter is characterized by losses, whereas in summer colony numbers increase. This model focuses on biannual changes that include winter losses, but also for the first time summer change rate, a hitherto understudied subject (van Engelsdorp and Meixner, 2010; Brodschneider and Crailsheim, 2011; Moritz and Erler, 2016). The 'summer change' rate is mostly characterized by the net increase of honey bee colonies through making splits or buying new colonies, but could exceptionally include decreases for single operations. Reduction in colony number during the summer season could derive from colony

Table 3
Number of beekeeping operations from Austria and Czechia providing complete data, winter loss rate of this subpopulation, colony numbers for the dates ‚previous spring', ‚previous autumn 'and ‚spring 'of years 2014 to 2017 are shown. ‚Summer change rate', ;spring-spring change 'and ‚spring-autumn estimation 'were calculated according to Fig. 1.

	Austria				Czechia			
Year	2014	2015	2016	2017	2014	2015	2016	2017
n	973	1188	1195	1537	556	959	951	1166
Winter loss of subpopulation (%)	12.9	28.6	7.9	22.5	6.6	19.4	6.3	14.9
Previous spring	14319	17355	15102	27695	8497	15557	13408	20940
Previous autumn	17816	21616	21800	40141	10458	19495	17050	24127
Spring	15518	15437	20070	31108	9772	15716	15969	20529
Summer change rate (%)	24.4	24.6	44.4	44.9	23.1	25.3	27.2	15.2
Spring-spring change (%)	8.4	−11.1	32.9	12.3	15.0	1.0	19.1	−2.0
Spring-autumn estimation (%)	14.8	40.0	8.6	29.0	7.0	24.0	6.8	17.5

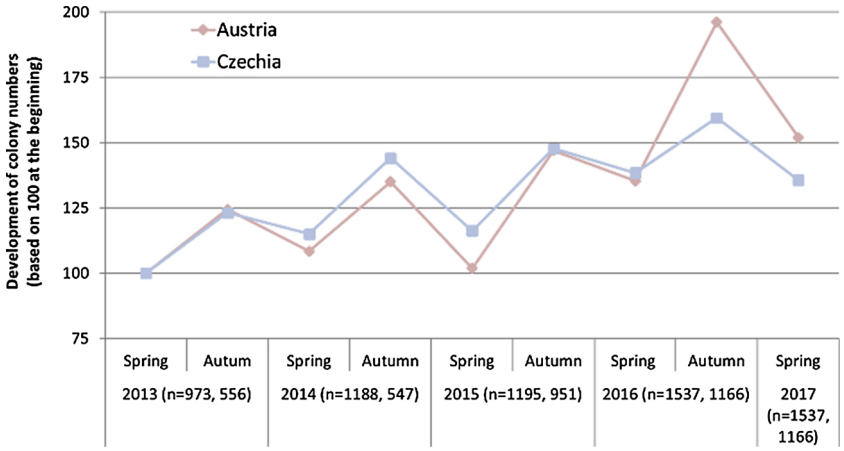


Fig. 6. Model development of temporal changes in honey bee colony numbers based on winter loss rates and summer change in Austria and Czechia 2014–2017. Change rates (see Table 3) were applied to 100 fictitious colonies in spring 2013 (n = number of operations in Austria and Czechia, respectively).

losses because of diseases, merging of colonies or selling of colonies, which could have different reasons. Next to biological reasons it could also be due the personal motivation of a beekeeper to reduce operation size. However, we applied the obtained 'winter loss' rates and 'summer change' rates on a fictitious population of 100 honey bee colonies. The result depicts the regular but fluctuating decreases during winter and (net) increases during summer (Fig. 6). 'Summer change rate' was between 15.2% and 44.9% and underlines the strong potential in apiculture to produce new livestock during summer.

Our findings clearly demonstrate that, although in some years many colonies are lost during winter, it is theoretically possible to increase the fictitious 100 colonies at the start to up to around 150 after 4 years, even considering losses during winter. Based only on losses during winter, followed by increase of honey bee colonies in summer, our model predicts a growing or at least stable number of honey bee colonies. We therefore suggest, that mechanisms other than colony losses and colony production by beekeepers additionally influence honey bee colony populations, that have in some countries or regions been reported to be declining (van Engelsdorp and Meixner, 2010; Brodschneider and Crailsheim, 2011; Moritz and Erler, 2016). For example, the socio-economic mechanisms related to the proportion of people in a country engaged in beekeeping deserve further research. This could, next to colony losses and increases, further elucidate our understanding of honey bee colony numbers in a country. Interestingly, the annual net increase in honey bee colonies is higher in Austria, compared to Czechia. In all four years of this investigation, Austria has suffered higher colony losses than Czechia. This finding therefore could be an adaption of Austrian beekeepers, who got used to higher losses and therefore make higher efforts during summer to maintain or even exceed colony numbers as reserve colonies or for sale. Notably, both countries exhibit the pattern, that low losses result in peak numbers of honey bee colonies, further supporting the hypothesis that reserve-colonies are being wintered. The fact that changes in colony stock numbers are rather moderate, as shown by the ‚spring-spring 'comparison in Table 3, underlines the importance of monitoring honey bee colonies losses to better understand dynamics of apiculture (Lee et al., 2015b; Kulhanek et al., 2017).

One limitation of our modelling approach is, that our methodology may include new beginners that contribute data, but people that quit beekeeping for whatever motivation, are not representated at all in our dataset. We therefore believe we slightly overestimate the upwards development of honey bee colonies as shown in this model. On the other hand, the number of officially registered colonies in Czechia increased by 40% between 2013–2016 (Table 1). This is consistent with our model, which suggests a 36% increase in number of colonies during the same time period (Fig. 6). Still, our analysis demonstrates the importance of understanding also the production of colonies during the active bee season to better react on threats to honey bee colony population. The parameter used in our model is a very rough approximation to the changes that honey bee colony stock numbers undergo, and we therefore deliberately do not speak about reproduction rates. The ‚summer change rate 'as defined in this study, only reflects net changes in colony numbers, no matter where the colonies come from or where they go to. It is therefore not clear, whether single operations

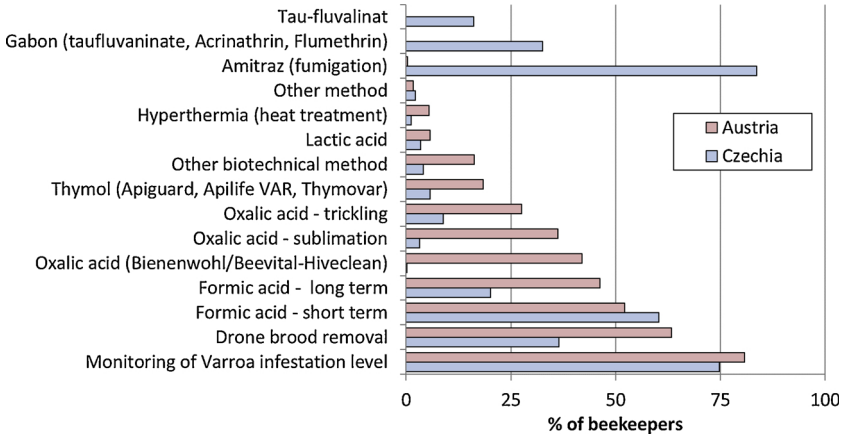


Fig. 7. Comparison of treatments against *Varroa destructor* used by Austrian (n = 4986) and Czech (n = 3688) beekeepers in the four investigated years. Percentage of beekeepers that applied the specified method in at least one month during the period April to April is shown.

sold or obtained any colonies to reach the number of colonies in autumn or produced them theirselves. As this renewal of honey bee livestock is at the work and financial expense of beekeepers, it is important to reduce colony losses for an economically sustainable apicultural sector. As suggested by our model, the situation in beekeeping may also be influenced by politics which financially support the beekeeping sector. Districts in Czechia stimulate citizens to start beekeeping with subsidies and flat-rate payments. The Czech national government updated § 10 from the Act No. 586/1992 Coll. in January 2014, which allows to keep up to 60 colonies without paying taxes. Similar efforts are undertaken in Austria. We believe that the biannual changes in honey bee colony livestock, we report here for Austria and Czechia, can be generalized for other countries with similar structural and climatic conditions.

Both study countries have different ways of registration of number of beekeepers and colonies. Whereas this is long established in Czechia, in Austria such a system has just been introduced recently. As we can only speculate about the coverage of the national registration systems, and the way of data collection differs from our voluntary study, comparison of the development of the officially registered honey bee colony populations and our results based on biannual changes must be made with caution. Further longitudal analysis of a subsample of (identifiable) beekeeping operations are recommendable. Our results on the high renewal of colonies during summer could provoke speculations about higher production rates of honey bee colonies as a result from winters with high losses. We therefore suggest further research aiming on the reasons for renewal on honey bee livestock and the exact way this is accomplished by beekeepers (Büchler et al., 2013).

4.4. Varroa fighting strategies in Austria and Czechia

Infestation of colonies with varroa mites and the methods to fight mites have strong effects on winter survival of honey bee colonies (Genersch et al., 2010; Rosenkranz et al., 2010; van der Zee et al., 2012, 2014; Giacobino et al., 2015). We present the first comprehensive survey data on strategies applied by beekeepers to fight *V. destructor*, which differ significantly between the two countries. In both countries, the majority of beekeepers do regularly monitor the infestation levels of their colonies (Fig. 7). To treat colonies, in Austria the majority of beekeepers follows the recommendation to evaporate formic acid after honey harvest and trickle or sublimate oxalic acid products in winter (Moosbeckhofer et al., 2015). In contrast to this recommendation of organic acids or essential oil treatments in Austria, the official authority State Veterinary Administration in Czechia recommends other obligatory treatments. Briefly, Czech beekeepers collect winter hive debris for examination of varroa mites before each spring, which is performed by offical laboratories. The debris from 10 colonies is pooled and mixed. If the debris sample contains more than 3 mites per colony, then spring *Varroa* treatment (with a product containing amitraz) is commanded. Summer treatment can also be commanded by authorities with Gabon strips (contains either tau-fluvanilate or flumethrin and till 2016 also acrinathrin). If there is no commanded treatment, there is still a recommendation for a summer treatment with any other registered product (based on formic acid or thymol; eAGRI, 2016). Autumn treatment is also commanded by veterinary authorities, the treatment is performed with Varidol 125 mg/ml (amitraz) or by other registered products (e.g. Formidol, Thymovar, Apiguard; ÚSKVBL, 2018). It was mandatory to treat the colonies 3x with fumigation of Varidol 125 mg/ml or MP10 (tau-fluvanilate) until 2013. Since 2013 Czech beekeepers have free choice in which product they will use, but the treatment in autumn remained obligatory. In contrast to this, use of synthetic acaricides is rather restricted in Austria.

As treatment strategy against the varroa mite is the most obvious difference in bee management, one is tempted to attribute the lower losses experienced in Czechia to the commanded treatments and use of synthetic acaricides. However, one needs to be careful with such declarations and final conclusions can only be made from controlled field trials. The two different strategies of *Varroa* control both have their advantages and disadvantages. These drawbacks include for example the risk of poor efficacy or undesired side effects on honey bees (Rosenkranz et al., 2010). Residues in the wax or honey, or growing resistance in mites, are drawbacks that concern mainly synthetic acaricides and their use should therefore be critcially evaluated. One such resistance, regarding the pyrethroid tau-fluvalinate, was recently investigated in Czechia (Stara et al., 2019), whereas it is longer known for Austria (Trouiller, 1998).

4.5. Conclusions

Honey bee health and colony losses are an international problem. We therefore underline the importance of internationally standardized data collection for to facilitate our understanding of the problem. In this article, we compare the apicultural sectors of Austria and Czechia, that have some similarities, but strongly differ for example in strategies to fight the varroa mite. In both countries, colony losses during winter were fluctuating from year to year, with strong regional differences. Winter losses related to queen problems occurr at rather stable and low levels. In both countries, we could in the last years successfully involve beekeepers as citizen scientists to collect quantitative data on a large scale. With this method, valuable long term data can be obtained, that allows further investigations of honey bee colony losses.

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APPENDIX 8

Varroa control strategies of different beekeeper groups and corresponding honey bee colony mortality in Central Europe

Journal of Advanced Research

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Under review

Journal of Advanced Research

Varroa control strategies of different beekeeper groups and corresponding honey bee colony mortality in Central Europe

--Manuscript Draft--

Manuscript Number:	JARE-D-25-07483
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Abstract:	Introduction The parasitic mite Varroa destructor remains a preeminent threat to Apis mellifera globally, contributing significantly to high colony losses despite varied control interventions. Understanding the diverse Varroa control strategies employed by beekeepers is crucial for mitigating these losses and improving bee health. Objectives This study aimed to comprehensively analyze the diverse Varroa destructor control strategies implemented by beekeepers across Austria, Czechia, Slovakia, and Poland, and critically evaluate their direct impact on honey bee winter colony mortality. Our primary objective was to identify and characterize optimal management practices that significantly enhance colony survival and provide evidence-based recommendations for regional Varroa control. Methods We analyzed 8,655 responses from over 171,756 colonies, collected via the COLOSS “Colony Losses Monitoring” survey during the 2019/20 and 2020/21 seasons. Beekeepers were categorized into small- (SB), medium- (MB), and large-scale (LB) groups. Treatment data, categorized into countries and four seasons, were evaluated. Decision tree analysis was applied to identify Best Treatment Strategies (BTS) resulting in the lowest winter colony losses for each country and beekeeper group. Results BTS varied significantly by country and apiary size. Most Czech, Polish, and Slovak beekeepers predominantly used synthetic acaricides in autumn, while Austrian beekeepers favoured organic acids year-round. Successful strategies consistently involved the timely and often combined application of biotechnological methods, organic acids, and acaricides. The lowest colony losses were consistently observed in large apiaries. Conclusion This study rigorously demonstrates that tailored Varroa destructor treatment strategies can substantially mitigate winter colony losses in Central Europe. The most effective strategies are characterized by the timely and synergistic integration of different

	treatments, rather than reliance on a singular approach. Consistently lower mortality in large apiaries underscores the pivotal role of structured management, accumulated experience, and diligent, multi-faceted treatment for robust Varroa control and sustainable colony health.

Varroa control strategies of different beekeeper groups and corresponding honey bee colony mortality in Central Europe

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Author contributions

Conceptualization: E.M., J.B., J.D.; Methodology: O.B., J.B., J.D.; Formal analysis: E.M., O.B., O.V.; Resources: R.B., R.C., A.G., J.B., J.D.; Writing – original draft: E.M., O.B.; Writing – review & editing: E.M., O.B., R.B., R.C., A.G., M.I., J.B., J.D.; Visualization: E.M., O.B., O.V.; Supervision: J.B., J.D.; Funding acquisition: E.M., J.D.

Conflict of interest:

The authors declare no conflict of interest

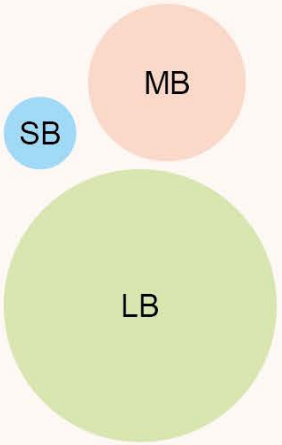
Compliance with Ethics Requirements

This study did not involve any experiments on animals or any interventional research on human subjects. Only fully anonymized questionnaire data from human participants were analyzed. The first page of the questionnaire included a full privacy and data-handling notice, and participants provided informed consent by completing the questionnaire. According to applicable regulations, this type of non-interventional and anonymous data collection does not require approval from an Ethics Committee. Data collection and processing complied with Regulation (EU) 2016/679 (GDPR) and the internal directive R-B-18/12 “Protection of Personal Data” of Palacký University Olomouc.

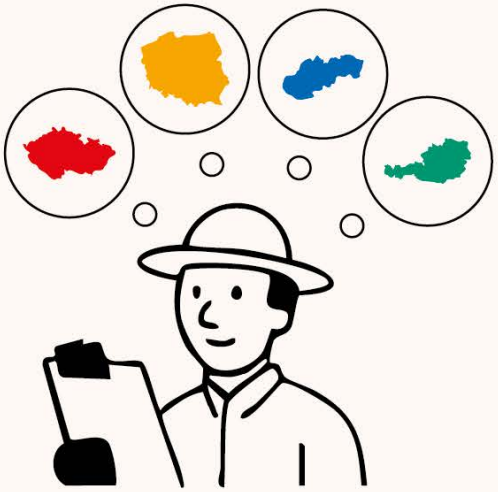
VARROA CONTROL STRATEGIES OF DIFFERENT BEEKEEPER GROUPS AND CORRESPONDING HONEY BEE COLONY MORTALITY IN CENTRAL EUROPE



Dominant treatment approaches vary by country



Best strategies differ by the scale of beekeepers



Advisory can be tailored to regional preferences



Available treatments reduce winter losses



Effective control depends on the method and timing

Highlights

- Decision trees allow to identify (minimal) Best Treatment Strategies (BTS) relevant for bee survival
- BTS vary by country and beekeeping operation size
- Most Czech, Polish and Slovak beekeepers use synthetic acaricides in autumn
- Austrian beekeepers predominantly apply organic acids year-round
- No universal method exists—success depends on timing and method combinations

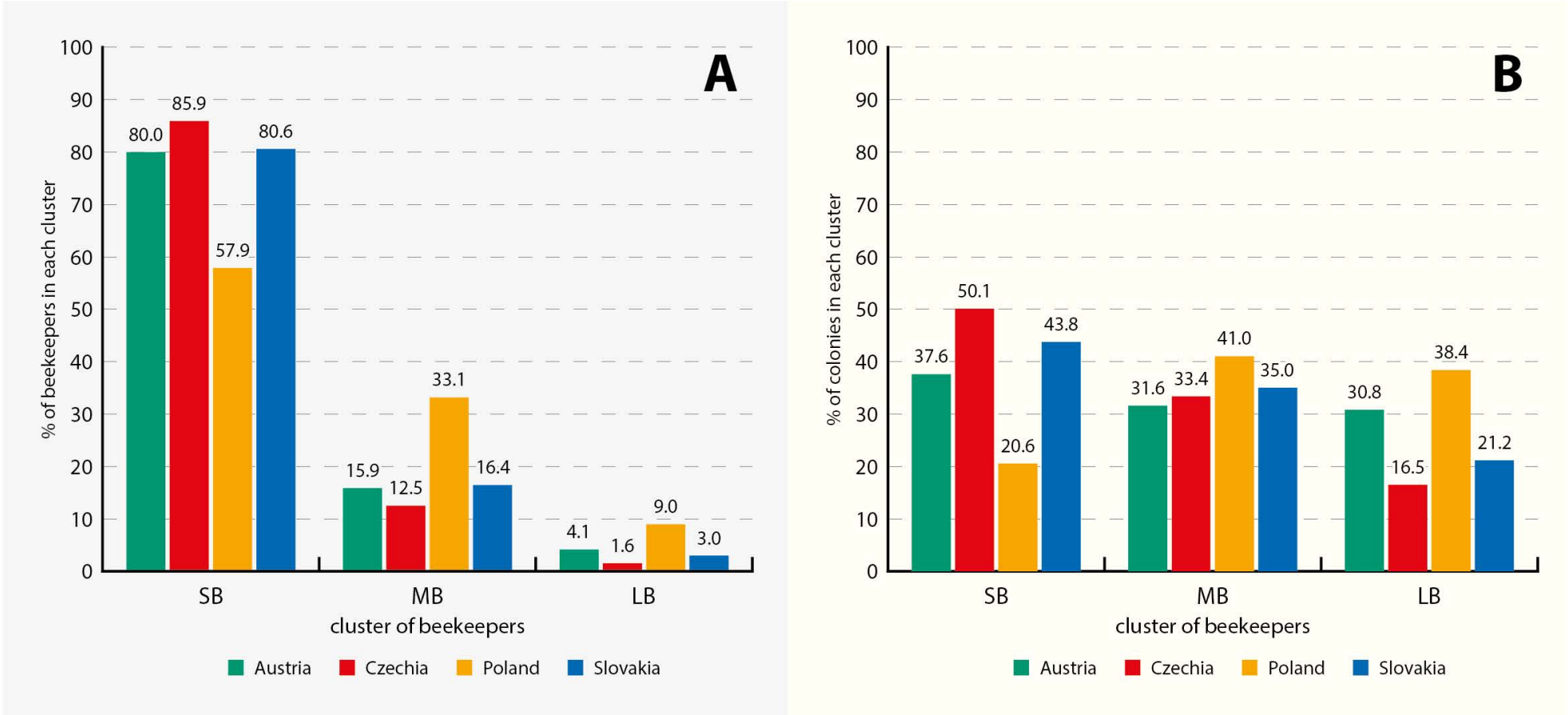

A
% of beekeepers in each cluster
100
90
80
70
60
50
40
30
20
10
0
80.0
85.9
57.9
80.6
15.9
12.5
33.1
16.4
4.1
1.6
9.0
3.0
SB
MB
LB
cluster of beekeepers
Austria
Czechia
Poland
Slovakia
B
% of colonies in each cluster
37.6
50.1
20.6
43.8
31.6
33.4
41.0
35.0
30.8
16.5
38.4
21.2
SB
MB
LB
cluster of beekeepers
Austria
Czechia
Poland
Slovakia

Figure 2 (300dpi and editable format)

Click here to view linked References

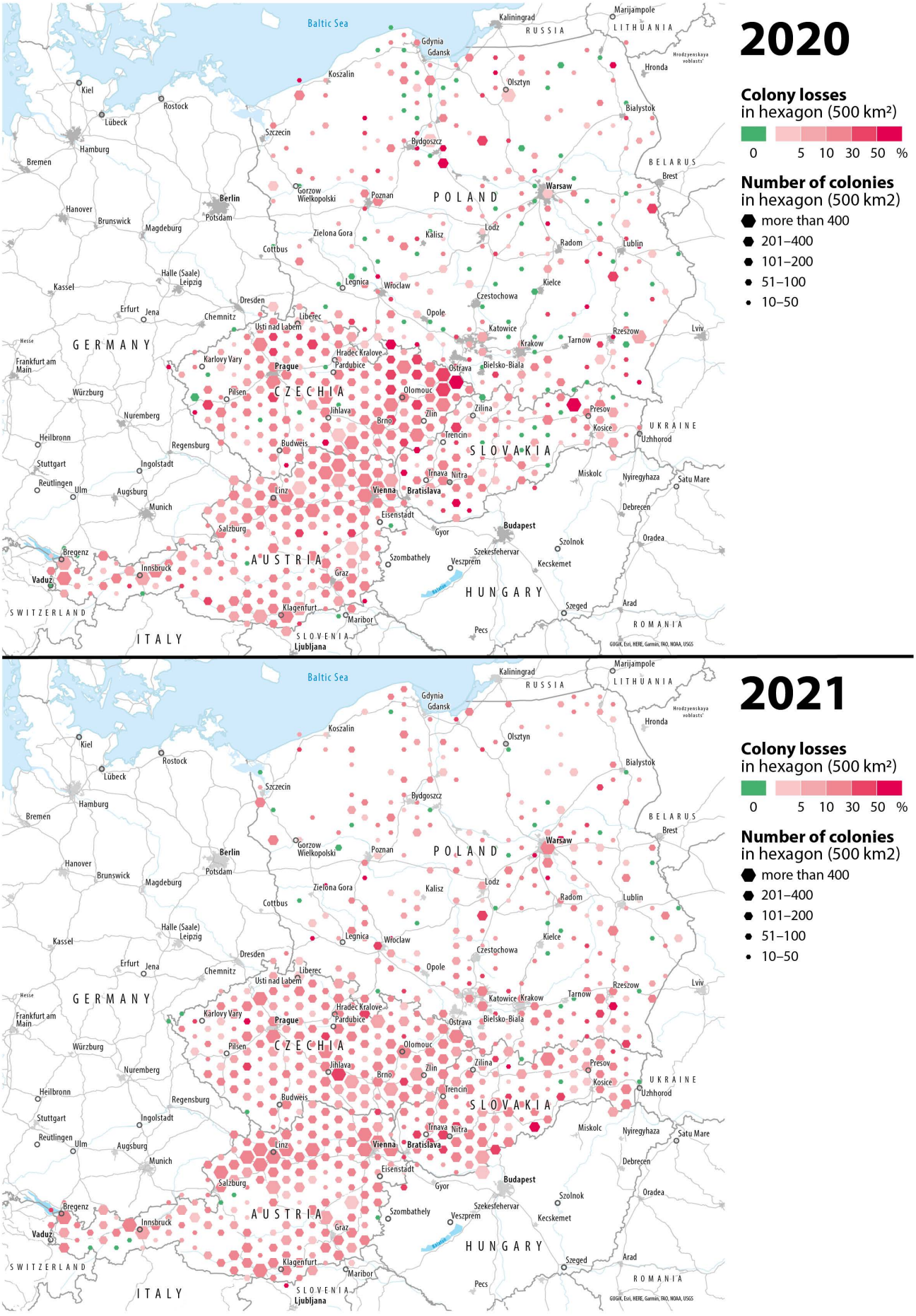
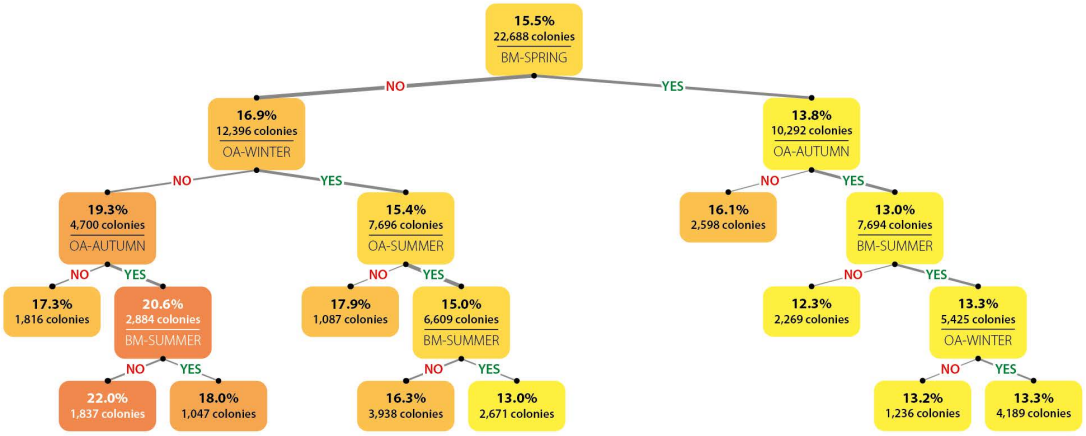


Figure 3 (300dpi and editable format)

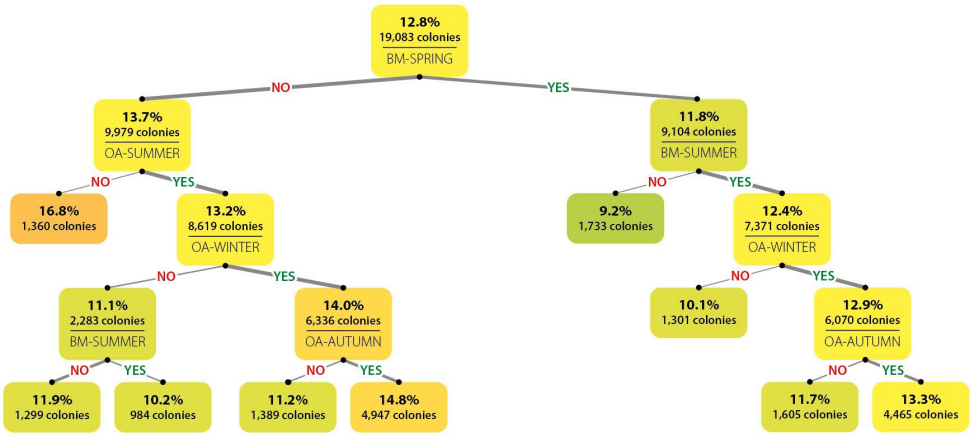
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AUSTRIA

Small-scale beekepers (SB)



Medium-scale beekepers (MB)



Large-scale beekepers (LB)

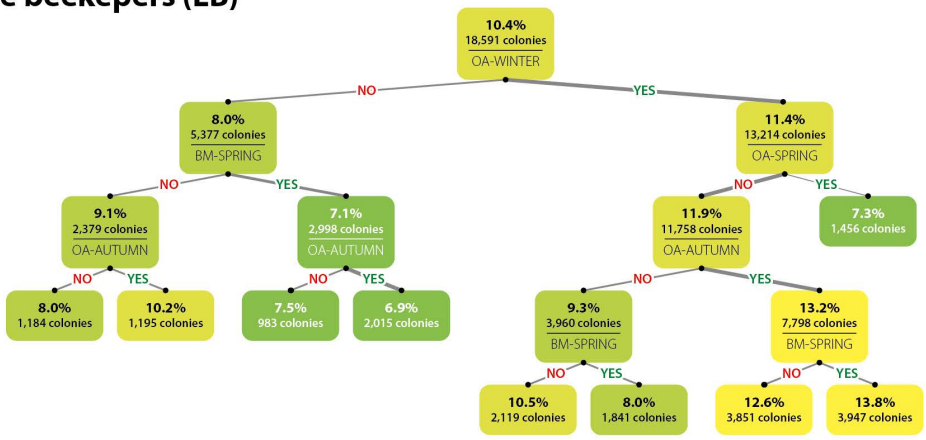


Figure 4 (300dpi and editable format)

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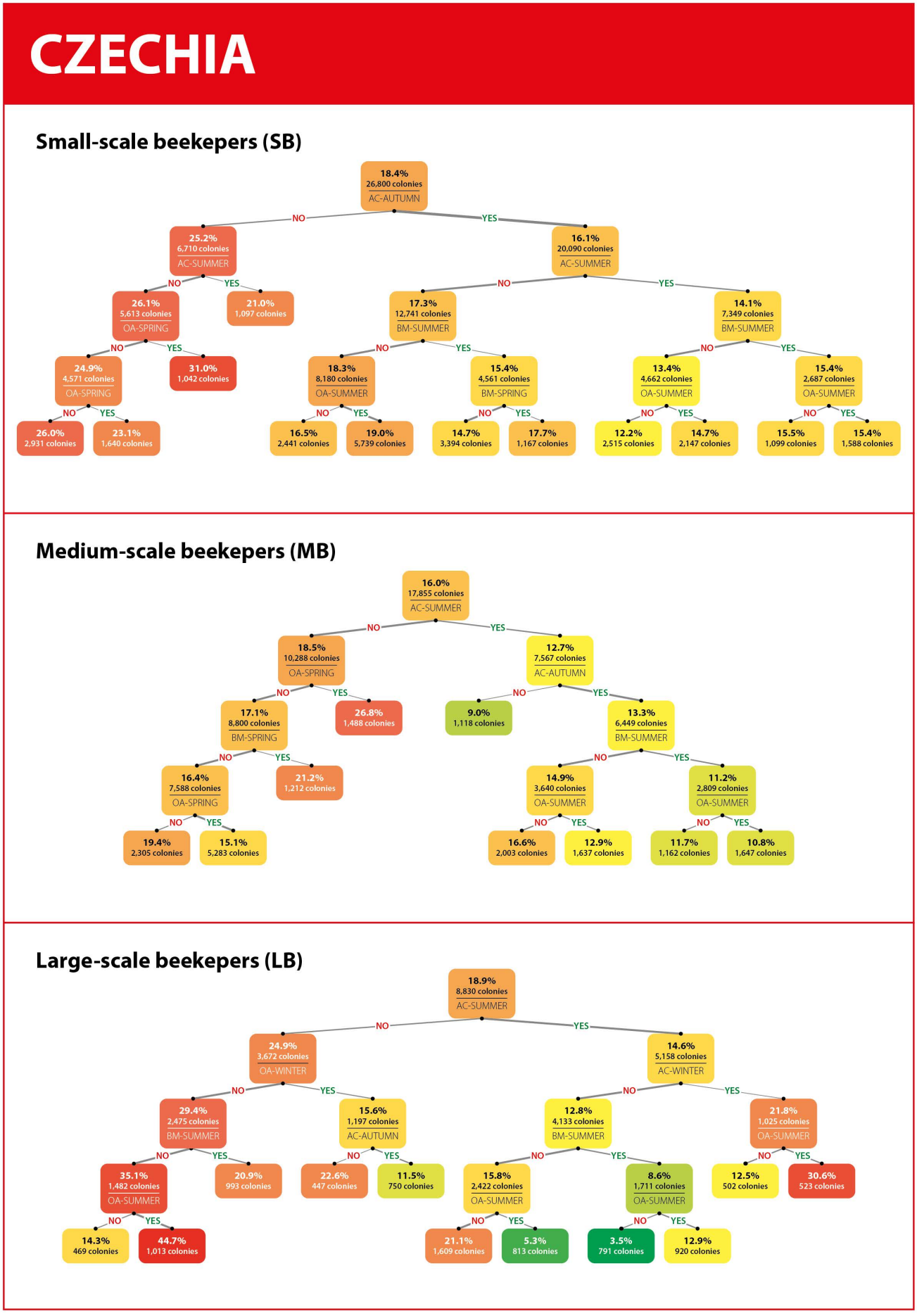
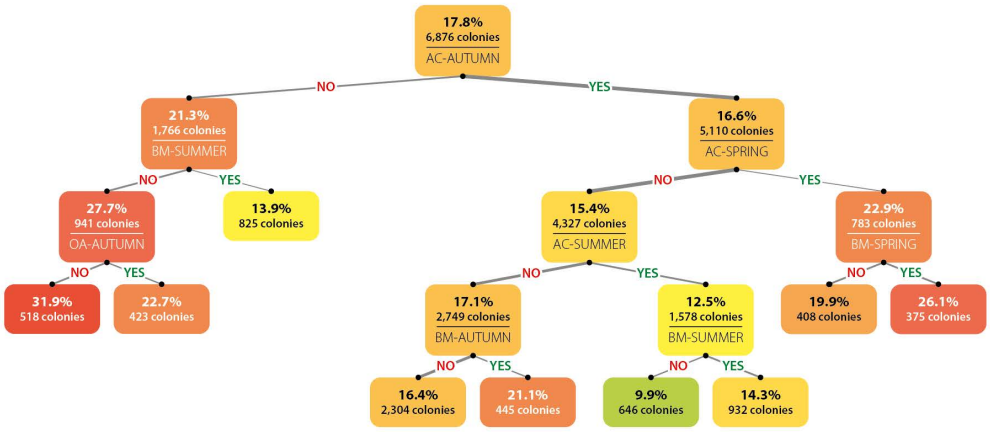


Figure 5 (300dpi and editable format)

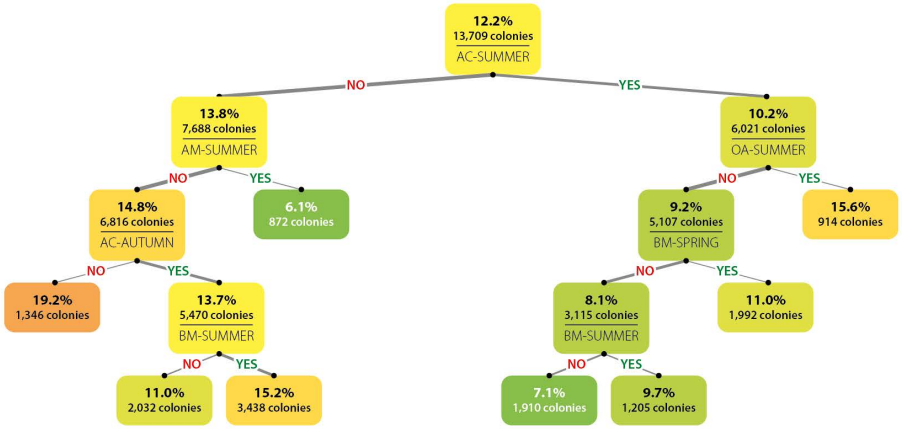
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POLAND

Small-scale beekepers (SB)



Medium-scale beekepers (MB)



Large-scale beekepers (LB)

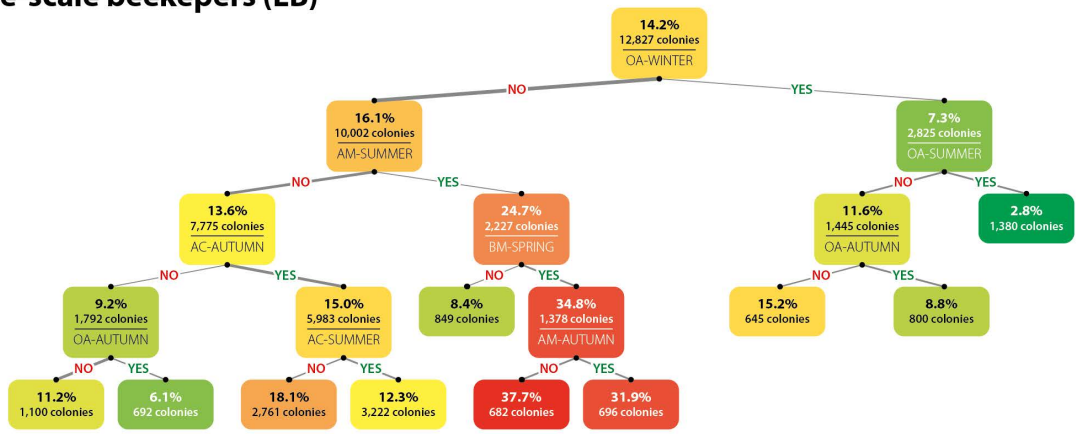
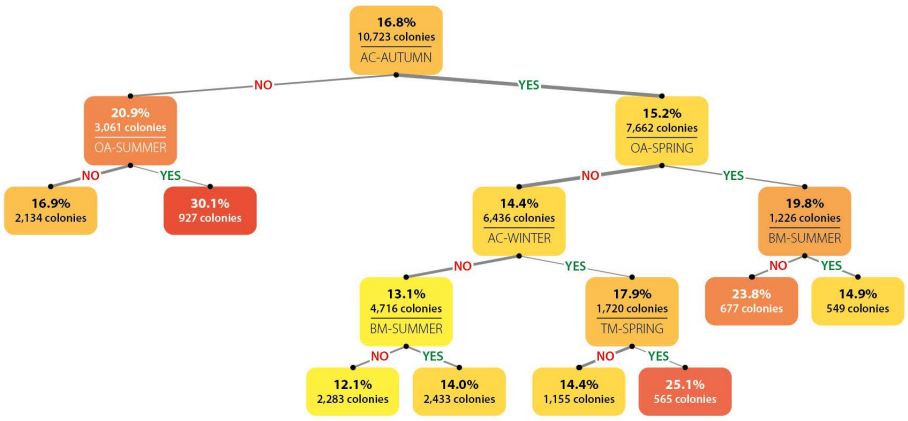


Figure 6 (300dpi and editable format)

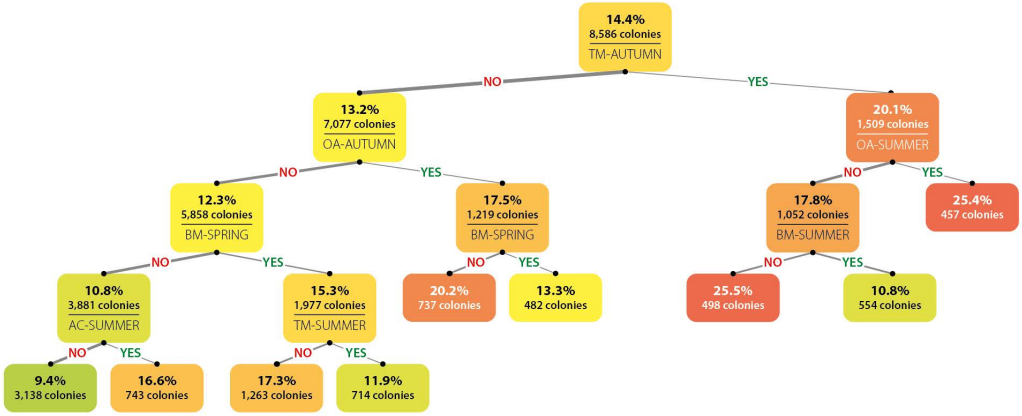
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SLOVAKIA

Small-scale beekepers (SB)



Medium-scale beekepers (MB)



Large-scale beekepers (LB)

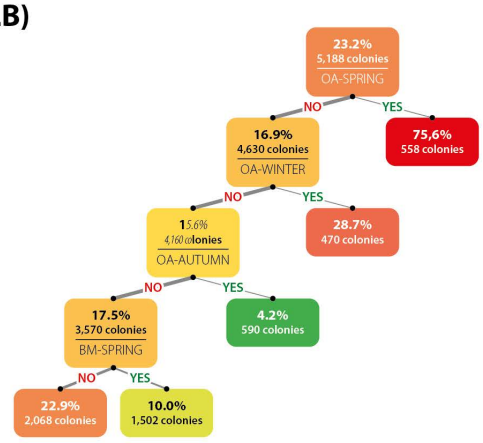


Table 1

Click here to view linked References

Name of treatment method	The treatment method merged into the category	Abbreviation
Biotechnical method	Drone brood removal, heat treatment, other biotechnical method (as e.g. trapping comb, complete brood removal, queen excluder, screened bottom board)	BM
Organic acids	Formic acid-short term (Formicprotect®, Formidol®), formic acid-long term, lactic acid, oxalic acid-trickling, oxalic acid-evaporation, commercial drugs with oxalic acid (Api-bioxal®, Oxybee®, Oxuvar®, Varromed®)	OA
Essential oils	Thymol and/or essential oils (Apiguard®, ApilifeVar®, Ekovartin®, Ekopol®, Thymovar®)	EO
Acaricides	Fluvalinate (Gabon PF 90®, MP 10 FUM®, M-1 AER®), flumetrin (Bayvarol®, Gabon Flum 4®, PolyVar Yellow®), amitraz strips (Apistrip®, Apivar®, Biowar®) amitraz fumigation (Apiwarol®, Avartin B-90®, Varidol Fum®)	AC
Another methods	Another method, another chemical method	AM

Table 2

Click here to view linked References

Factors			Relative frequency				
season	**country**	**average percentages of treatments**	**OA**	**AC**	**BM**	**EO**	**AM**
SPRING	Austria	4.1	5.47**	0.03*	43.53*	0.2*	0.44*
	Czechia		15.54*	2.39*	12.55*	0.49*	0.2*
	Poland		9.91*	15.12*	38.89*	2.5***	7.09*
	Slovakia		14.64*	3.29	35.55*	24.35*	1.88*
SUMMER	Austria	15.98	79.76*	1.36*	50.42*	4.96*	1.39*
	Czechia		61.49*	31.09*	32.44*	4.26*	0.37*
	Poland		20.33*	37.85*	57.77*	5.53*	9.28*
	Slovakia		35.63*	16.76	41.11*	36.88*	2.74*
AUTUMN	Austria	9.96	70.46*	1.12*	2.34*	4.24*	0.61*
	Czechia		28.27*	73.46*	5.18*	2.85*	0.35*
	Poland		22.63*	74.35*	11.37	5.21*	7.3**
	Slovakia		22.32*	67.66*	3.68*	22.47*	2.19*
WINTER	Austria	2.02	69.51*	0.27*	0.14*	0.81*	0.24*
	Czechia		14.65*	16.12*	0.46*	0.29*	0.52*
	Poland		7.3*	8.65*	2.29	0.63**	0.94***
	Slovakia		9.32*	21.69*	0.47*	2.43	1.41

Table 3

Click here to view linked References

Country	Cluster	Colonies treated by BTS[a]	Initial loss rate (%)	Predicted loss rate (%)	OA				BM		AC				EO	AM
					SPRING	SUMMER	AUTUMN	WINTER	SPRING	SUMMER	SPRING	SUMMER	AUTUMN	WINTER	AUTUMN	SUMMER
AUSTRIA	SB	10%	15.5	12.3			✓		✓	✗						
	MB	9%	12.8	9.2					✓	✗						
	LB	10.8%	10.4	6.9			✓	✗	✓							
CZECHIA	SB	9.4%	18.4	12.2		✗				✗		✓	✓			
	MB	6.3%	16	9								✓	✗			
	LB	9%	18.9	3.5		✗				✓		✓		✗		
POLAND	SB	9%	17.8	9.9						✗	✗	✓	✓			

	MB	6.4%	12.2	6.1											✗					✓
	LB	10.7%	14.2	2.8		✓		✓												
SLOVAKIA	SB	21%	16.8	12.1	✗					✗						✓	✗			
	MB	36.5%	14.4	9.4			✗		✗				✗					✗		
	LB	11%	23.2	4.2	✗		✓	✗												

Abstract

Introduction

The parasitic mite *Varroa destructor* remains a preeminent threat to *Apis mellifera* globally, contributing significantly to high colony losses despite varied control interventions. Understanding the diverse *Varroa* control strategies employed by beekeepers is crucial for mitigating these losses and improving bee health.

Objectives

This study aimed to comprehensively analyze the diverse *Varroa destructor* control strategies implemented by beekeepers across Austria, Czechia, Slovakia, and Poland, and critically evaluate their direct impact on honey bee winter colony mortality. Our primary objective was to identify and characterize optimal management practices that significantly enhance colony survival and provide evidence-based recommendations for regional *Varroa* control.

Methods

We analyzed 8,655 responses from over 171,756 colonies, collected via the COLOSS "Colony Losses Monitoring" survey during the 2019/20 and 2020/21 seasons. Beekeepers were categorized into small- (SB), medium- (MB), and large-scale (LB) groups. Treatment data, categorized into countries and four seasons, were evaluated. Decision tree analysis was applied to identify Best Treatment Strategies (BTS) resulting in the lowest winter colony losses for each country and beekeeper group.

Results

BTS varied significantly by country and apiary size. Most Czech, Polish, and Slovak beekeepers predominantly used synthetic acaricides in autumn, while Austrian beekeepers favoured organic acids year-round. Successful strategies consistently involved the timely and often combined application of biotechnological methods, organic acids, and acaricides. The lowest colony losses were consistently observed in large apiaries.

Conclusion

This study rigorously demonstrates that tailored *Varroa* destructor treatment strategies can substantially mitigate winter colony losses in Central Europe. The most effective strategies are characterized by the timely and synergistic integration of different treatments, rather than reliance on a singular approach. Consistently lower mortality in large apiaries underscores the pivotal role of structured management, accumulated experience, and diligent, multi-faceted treatment for robust *Varroa* control and sustainable colony health.

Keywords

Apis mellifera, colony losses, *Varroa destructor,* acaricides, Integrated Pest Management, treatment strategies

Introduction

The parasite *Varroa destructor* is one of the main causes of honey bee (*Apis mellifera*) colony losses worldwide [1], and it has a detrimental effect on colonies on many levels [2]. Female mites that feed on the pupating bee cause them to lose haemolymph, atrophy of the fat body, and weight loss. As a consequence, newly emerged bees have a decreased capability of learning, shorter life-span, altered flight and orientation, and reduced sperm production in drones [2,3]. *V. destructor* also affects honey bees' immune response [2,4]. This parasite is a vector of viruses and has contributed to their global spread [5], e.g. deformed wing virus (DWV) or acute bee paralysis virus (ABPV). Heavy-infested colonies are slower to develop, produce less honey, and queen supersedure occurs more often [3]. Finally, parasitic mite syndrome (PMS) is visible on the brood, a lot of workers have crippled wings, and dead pupae lay in the front of the hive. Colonies without *V. destructor* control die within 1–3 years [3], and with viral co-infection, even earlier. Additionally, several studies have demonstrated that varroosis with other pathogens or pesticides has a more serious impact on honey bee health [6]. Researchers also proved that severe *V. destructor* infestation with viral co-infections causes high winter colony losses [7–9]. Honey bees are one of the most important pollinators, their survival rate is economically important [10].

The monitoring of colony losses allows us to identify factors that influence colony mortality. Risk factors for colony losses are not only varroosis but also *Nosema* spp. infection [11], beekeeping management-related factors [12–14], and other abiotic agents [15–17]. Nevertheless, effective control of *V. destructor* is critical to maintaining healthy bee populations, especially in Europe and North America, where managed subspecies do not show widespread tolerance. Additionally, temperatures due to increasing climate change affect beekeeping [18,19].

The European Union veterinary drugs against varroosis list includes 12 active substances and 7 drug formulations [20]. Treatment is carried out mainly by beekeepers and not by veterinarians. Therefore, there is a certain flexibility in using veterinary medicines, and many errors in their administration occur (e.g., overdose, underdose, lack of chemical rotation, mixing drugs). Many beekeepers still treat their bees only once a year [21], mainly in late summer or autumn, which can result in high mortality during winter, whereas proper treatment should include preventive measures throughout the season and the use of control methods based on *V. destructor* monitoring [22]. As treatment without following the drug instructions is dangerous for bee safety and bee product quality [23], there is also a risk of mites' resistance to synthetic active substances [24,25]. Studies have shown that different beekeepers use varied treatment strategies, impacting colony losses [26–28]. The studies suggest that commercial beekeepers with large apiaries are more likely to use synthetic acaricides and have lower colony mortality. In contrast, small-scale beekeepers are more inclined to use organic substances and combined methods, and have higher colony losses, though this might be correlated but not linked [14,29,30]. This is related to management objectives, different beekeeping philosophies, and also knowledge [29,31]. Different treatment patterns exist in Europe [21], but a lack of data shows varied varroosis control strategies in the context of specific beekeeping groups.

This paper aims to identify how different *V. destructor* control strategies affect colony survival in small, medium, and large-scale beekeeping operations. We identified key differences in treatment choices among beekeeping groups in Central Europe and showed their influence on overall winter loss rates. The objectives of the study are to provide data-based recommendations to a specific group of beekeepers and contribute to improving the guidelines for successful control of varroosis.

Materials and methods

We collected data through a crowdsourcing effort established by the COLOSS Core Project 'Colony Losses Monitoring' [12]. Every year, the COLOSS standardized questionnaire (Supplementary File S1) is launched after the overwintering period in local languages. The survey is open online for 2–3 months (from April to May or June). These surveys were carried out in Austria, Czechia, Poland, and Slovakia in the 2019/20 and 2020/21 seasons according to GDPR. The following data were extracted from national codebooks and used in this study: 1) the ZIP code of the operation; 2) the city closest to the main apiary 3) the number of production colonies before winter in all apiaries of the operation; 4) the number of lost colonies in the operation; 5) the type of treatment method against *V. destructor* and the month of use. Beekeepers could choose from 18 possible treatment methods during 12 months (from March in the year before winter to April in the year after winter, e.g., March 2019 to April 2020). The database was created in Microsoft Excel (Microsoft® Excel® 2019 MSO). Before analyses, the database was checked for double and incomplete or illogical answers.

We merged treatment methods into five categories based on the drug's active substance or the type of treatment (Table 1) and pooled months into 4 seasons (Supplementary File S2, Table S1). Each country's overall winter colony loss rate was calculated as the number of lost colonies after winter divided by the number of all production colonies before winter.

Based on the number of colonies in each apiary, three beekeeping clusters were identified: ≤25 colonies – small-scale beekeepers (SB), 26-80 colonies – medium-scale beekeepers (MB), ≥80 colonies – large-scale beekeepers (LB) in each country. The percentage of beekeepers, respectively colonies in each cluster per country, was

calculated as the number of beekeepers and colonies in each cluster divided by all beekeepers or colonies in the country. Figures were created in Adobe Illustrator from Adobe Creative Cloud Bundle.

ZIP codes and the nearest cities to the apiaries were geocoded to obtain point features, which were then used in ArcGIS Pro for spatial analysis. These point features created maps showing the colony density and winter loss rates. To ensure comparability regarding density values, we created a hexagonal grid covering the entire research area, with each hexagon representing an area of 500 km^2. By overlaying the point features with this hexagon grid, we were able to sum up the number of wintered colonies and the colonies lost during winter within each hexagon. This process resulted in a hexagonal grid containing two key attributes: the number of wintered colonies and the number of lost colonies during winter. Using these two attributes the colony loss rate was calculated. The loss rate and the number of wintered colonies are presented together using multidimensional visualizations. The colony loss rate is visualized by colour, and hexagon sizes show the number of colonies, helping to visualize the heterogeneity in hives' locations.

Statistical analysis:

We analyzed the differences in the use of different types of treatment among individual countries. The two-year databases were combined to obtain descriptive statistics and analyses of treatment strategies. The likelihood that a specific treatment is used depends on the following factors: 1) treatment (OA: organic acids, AC: synthetic acaricides, BM: biotechnological methods, EO: essential oils, AM: another methods); 2) season (spring / summer / autumn / winter); 3) country (Austria / Czechia / Poland / Slovakia); 4) year; 5) beekeeping cluster (SB, MB, LB). For each season, an ordered

quintuplet (Y1,...,Y5) consisting of zeros and ones represents the usage of five possible treatments of a certain beekeeper. Its individual values correspond to OA, AC, BM, TM, and AM, respectively. The binary variables Y1,...,Y5 are correlated since the usage of a specific treatment influences the possibility/necessity of the usage of other treatments. A so-called exchangeable correlation structure is assumed. The basic marginal logit model has the following form:

$$\text{logit}[P(Y_i = 1)] = \beta_0 + \beta_i^{treat} + \beta_c^{country} + \beta_y^{year} + \beta_b^{bk},$$

where upper indices of parameters beta denote factors to which the parameters are related and lower indices denote individual categories of the factors (i =1,…,5, for five categories of the treatment, c =1,…,4, for four countries, y =1,2, for the two years, and b=1,…,3, for three distinguished groups of beekeepers). Sum contrast coding is used. Therefore, the intercept corresponds to the geometric mean of chances, while individual parameters describe deviations from this mean. If needed, interaction terms are added to the basic model.

The parameters are estimated using the generalized estimating equations (GEE) approach. The significance of individual effects is tested using Wald statistics. Statistical analysis was performed in R software (version 4.3.2) using geepack [32,33].

The decision trees were created in the Orange Data Mining software (version 3.37.0, free software under the terms of the GNU General Public License) [34]. Three decision trees were created for each country for SB, MB, LB. The minimum number of colonies in the last leaf (last category at the bottom of the tree) was established to be 5% of all colonies in the cluster (e.g., if there are 10,000 colonies in total, the last leaf should have at least 500 colonies). Each decision tree has five levels of branches. In each decision tree, we highlighted the path leading to the lowest winter colony loss rate and

considered it to be the best treatment strategy (BTS). BTS shows the treatment steps taken by beekeepers in each season (whether they used or did not use the methods). As we merged data from two years, the algorithm does not indicate the order of treatment, and leaves do not indicate the year of the treatment. The algorithm does not indicate that respondents did not use any other treatment outside the BTS. The result of the decision tree was the average winter colony loss rate (in %) from the two years combined highlighting the most significant treatment methods whose (non-)use affects the reduction / increase in the resulting colony loss. The percentage of colonies treated by BTS was calculated as the number of all colonies reported in a cluster divided by the number of colonies treated with the strategy. Original data are available as Supplementary File S3 for Austria, S4 for Czechia, S5 for Poland, and S6 for Slovakia.

Ethics statement

This study did not involve any experiments on animals or any interventional research on human subjects. Only fully anonymized questionnaire data from human participants were analyzed. The first page of the questionnaire contained a full privacy and data-handling notice, and participants provided informed consent by completing the questionnaire. Data collection and processing complied with Regulation (EU) 2016/679 (GDPR) and the internal directive R-B-18/12 “Protection of Personal Data” of Palacký University Olomouc.

Results

Study population and distribution of registered colonies

A total of 8,655 answers on 171,756 honey bee colonies from 4 countries were collected. SB dominated in all countries (Fig. 1A). The percentage of colonies managed

by MB and LB was highest in Poland (41.03% and 38.39%, respectively). In Austria, the percentage of colonies was relatively equal for every cluster (from 30.8% to 37.59%) (Fig. 1B), even though most beekeepers were in SB.

The overall winter colony loss rates were above 10% in all seasons in each country. Honey bee colony loss rates in Austria, Poland, and Slovakia were found to be similar (Supplementary File S2, Table S2) [12]. Higher losses occurred in Czechia, where the 2019/20 loss rate was 20.8%.

The distribution of colony losses and the number of colonies reported in each season (2019/20, 2020/21) are shown in Fig. 2.

*Differences in the V. destructor treatment use*d

The average percentages of treatments applied in different seasons for the whole study population were 4.1% for spring, 16.0% for summer, 10.0% for autumn, and 2.0% for winter (Tab. 2). The interaction between country and treatment was significant in each season, indicating that the application of treatments varies considerably between countries (Tab. 2).

In Austria the use of BM was above the average in spring and summer and below the average in autumn and winter (Tab. 2). OA treatment was above average in all seasons. The relative frequencies were higher than in the other countries. The use of EO, AC and AM treatments was below the average in all seasons.

In Czechia the use of BM was above the average in spring and summer and below the average in autumn and winter. The use of OA treatment was above the average in all seasons. The use of EO and AM treatment was below the average in all seasons. AC

use was above the average in summer, autumn and winter, but below average in spring. The relative frequency of AC treatment in autumn reached 73.5% (Tab. 2).

In Poland the use of BM was higher than average in spring and summer and equal to average in autumn and winter. OA use was above the average in all seasons. The use of EO was below average in all seasons. AC use was above the average in all seasons. The use of AM treatment was below the average in summer, autumn, and winter, but above average in spring, reaching 7.1%, in contrast to other countries (Tab. 2).

In Slovakia, the use of BM was above the average in spring and summer and below the average in autumn and winter. OA use was above the average in all seasons. The use of EO was above the average in all seasons, with the exception of winter, where it was insignificant. The use of AC was above average, but only in autumn and winter, but not significantly in spring and summer. The use of AM treatment was below the average in spring, summer, and autumn, but not significant in winter (Tab. 2).

The factor year was insignificant in any of the four models, indicating no significant differences in treatment administration between the two years under consideration (2019/20, 2020/21).

The operation size factor was not statistically significant in spring and autumn. However, in summer, treatment use in SB was 21% below the average ($p < 0.001$), while it was significantly above average in MB and LB operations by 7% ($p = 0.024$) and 18% ($p = 0.001$), respectively. In winter, treatment use in SB remained below average by 14% ($p = 0.001$), was 11% above average in LB ($p = 0.040$), and showed no significant difference in MB.

Decision trees

The decision tree analysis identified treatment combinations (BTS) that most effectively reduced winter colony losses in SB, MB, and LB across Austria, Czechia, Poland, and Slovakia. These strategies varied substantially between countries and beekeeper clusters. The percentage of colonies treated with BTS varied widely between countries and clusters (from 6.3% in Czechia for MB to 36.5% in Slovakia for MB) (Tab. 3).

Austria

Austrian beekeepers relied on OA and BM, which formed all BTS. In SB operations, the use of BM in spring combined with OA in autumn, and not using BM in summer resulted in a 12,3% loss rate. MB used BM in spring and not used BM in summer (Fig. 3). A similar pattern of treatment is visible in LB, who achieved the lowest loss rates. The strategy based on organic acid treatment, combined with BM in spring, tended to decrease colony loss rates.

Czechia

In Czechia AC, were commonly used and formed the core of effective BTS for all clusters. Among SB, a combination of AC in summer and autumn (while avoiding BM and OA in summer) resulted in 12.2% winter losses. MB used only AC in summer and not used AC in autumn resulting in 9.0% loss rate, whereas LB achieved the best outcome (3.5% loss rate) combining AC and BM (Fig. 4). These findings emphasize the benefit of integrating biotechnical and chemical strategies while avoiding unnecessary OA application.

Poland

Polish BTS showed the greatest variability across clusters. In SB, the use of AC in summer and autumn, combined with its omission in spring and BM summer, resulted in a moderate reduction of winter loss (9.9%). In contrast, MB achieved a significant reduction (6.1%) using AM during summer, without AC in summer. The most successful BTS was observed in LB, where combining OA in winter and in summer yielded an exceptionally low winter loss of 2.8%, i.e. the lowest among all groups in the study (Fig. 5). These outcomes suggest high efficacy of well-timed organic and biotechnical treatments among professional operations.

Slovakia

Slovakian BTS varied notably between clusters. SB benefited from AC application in autumn, while avoiding OA in spring, AC in winter, and BM in summer. MB strategies involved avoiding treatments with EO and OA in autumn, and BM in spring, and AC in summer, achieving 9.4% loss. The best-performing strategy was found among LB, who used OA in autumn while avoiding OA in spring and winter, resulting in 4.2% loss (Fig. 6). The Slovak data suggest that treatment avoidance at inappropriate times is equally important as treatment application at the right ones.

Discussion

The increased losses of bee colonies in Europe are a documented phenomenon, although the situation varies yearly [12,35]. However, the number of bee colonies now increases slightly, in contrast to previous decades [36,37]. This growth is driven mainly by a significant increase in Southern Europe, while Central regions show a mixed picture, with declines or stagnation among small-scale beekeepers.

One of the limits of further development is the health of honey bees, which are struggling with a pandemic of viruses, bacterial diseases, fungal diseases, and parasites [3,5,11,38]. *V. destructor* is one of the most widespread threats to honey bees [1]. As mentioned, several veterinary drugs to control parasitic mites are available. Researchers emphasize that there is a need for new active compounds to control varroosis efficiently [2]. On the other hand, the Integrated Pest Management method (IPM), which combines biotechnical methods and "old" active substances (i.e. amitraz, flumethrin and τ-fluvalinate), is efficient [22,39]. Nevertheless, any treatment against *V. destructor* is associated with lower winter colony losses [9,14,26].

This is the first study where the classification tree was used to establish the most effective treatment against *V. destructor* in honey bee colonies. We aimed to identify specific treatment steps called Best Treatment Strategy (BTS) that lead to the lowest winter losses, considering the size of the beekeeping operation. The analysis confirmed that no universal treatment strategy exists; however, almost all BTS had one commonality: structured, multi-seasonal application of treatments, often combining biotechnical and chemical approaches. In all countries, BTS was used by only a small percentage of beekeepers in each cluster (Tab. 3), which may mean that many other beekeepers follow less successful concepts or treat inefficiently. The winter loss rate achieved with BTS in each group was less than 13%, which is widely accepted loss rate [8]. Moreover, the lowest loss rates were in LB in all countries (Tab. 3).

According to Jacques et al. [40], the larger the operation, the broader the knowledge of the beekeepers. Researchers found that colony mortality is lower in commercial apiaries (commonly more than 80-150) because of the beekeepers' knowledge, experience, and professionalism [9,12,26,31,35,40]. More experienced beekeepers

have less time to check on their colonies and monitor bee health, while hobbyist beekeepers care for each colony individually, inspect their hives longer and more frequently, and have more time for monitoring [28]. Despite this, they have higher losses [14,41].

We assumed there would be significant differences in seasonality of treatment between operation size clusters, but only in summer and winter MB and LB treated significantly more often than SB. SB may still treat colonies before and at the end of the season, avoiding treatment just after honey harvest (summer) and at a lower temperature (winter). Nevertheless, in this study, SB using BTS reached colony losses lower than 13%. Thus, we can conclude that available treatment methods allow all beekeepers to control *V. destructor* effectively.

In three countries (Czechia, Poland, and Slovakia), the BTS for SB included the use of AC in autumn and in two countries (in Czechia and Poland) AC in summer (Tab. 3, Fig. 4-6). Secondly, the algorithm also determined not using AC in winter in Slovakia and not using AC in spring in Poland. In fact, using AC is present in other beekeeping clusters (MB and LB) only in Czechia. Mite resistance to AC, including tau-fluvalinate, flumethrin (cross-resistance to tau-fluvalinate), and coumaphos, has already been demonstrated [42–44]. In recent years, reports of emerging mite resistance to amitraz [45], one of the most widely used synthetic acaricides against *V. destructor* [21], have been of great concern. However, our result suggests that these drugs are widely used in Czechia, Poland, and Slovakia and still effective in reducing colony mortality (Tab. 2). Furthermore, although the use of BM was above average of treatment in spring and summer in all countries (Tab. 2), their use was only included in the BTS in Austria and Czechia (Fig. 3, 4). Interestingly, the algorithm determined not to use BM in all SB decision trees in summer. This is in contrast to the recommendation of BM in IPM,

especially for summer brood interruption, where a variety of methods are available [22,46]. We can assume that SB may need more instructions and training to best apply BM [40]. Brodschneider et al. [21] found that drone brood removal (included in our list of BM) was one of the most popular treatments in Europe, and this method can be ineffective [47].

Austrian beekeepers have a long tradition in using organic acids [21]. The results of our study also confirm the importance of OA in Austria (Fig. 3), but the algorithm indicated the use of OA only in autumn (for SB and LB) and not in winter. Interestingly, in other countries, OA were mainly not included or indicated as “do not use” in decision trees (Tab. 3), even if they were used above average from spring to winter (Tab. 2). This could be due to different ways of OA application, i.e. trickling (with or without sugar), spraying, or sublimating, which were not differentiated in our study. OA were present only in LB in Poland and Slovakia BTS’s, so we conclude that professional beekeepers applied this organic treatment more effectively. This is also visible in Czech decision trees for MB and LB, where pathways with OA also lead to one of the lowest losses (Fig. 4). Interestingly, the application of OA in spring and summer was often associated with higher losses, particularly in Czechia and Slovakia, indicating the importance of careful seasonal planning and correct application in broodless colonies [39]. Additionally, repeated treatment with OA can cause colony stress or damage if done too often during spring and summer [48].

We should also note that authorized medications with organic acids are among the most expensive on the market, and beekeepers often use their homemade form. Non-authorized formulations, such as oxalic acid strips, may have lower efficacy [23,49], and they may induce humoral immune responses in adult bees [50]. As Polish beekeepers use preparations outside the official list of available veterinary drugs, the

Polish BTS for MB is of great concern because it only includes the use of AM in summer and not AC in summer (Fig. 5). Further studies are needed to specify which methods are really used by beekeepers. Strategies in different operation size clusters in Poland were very different, but all resulted in a satisfactory survival rate (Fig. 5). A possible reason for this could be the profound discrepancies in beekeeping management due to experience, education, and source of knowledge. A similar situation occurred in Slovakian decision trees, with no similarities between clusters (Fig. 6). Although EO were more often used than in other countries, they were not present in the BTS in either SB or LB (Tab. 2, 3). In addition, the decision tree for MB includes not using EO in autumn. EO in autumn was placed as the first step by the algorithm, and most beekeepers selected “not using” (Fig. 6), so we can conclude that the popularity of EO in Slovakia continues to grow. Finally, both the Austrian and Czech BTS are quite homogeneous across operation size clusters. This may be linked to national recommendations for beekeepers from AGES in Austria and the State Veterinary Administration in the Czech Republic. Therefore, if beekeepers are obliged to treat simultaneously with the same method, treatment may be more effective, and reinvasion of *V. destructor* is less likely [48].

Our study confirmed the spatial distribution of *V. destructor* control strategies in Central Europe demonstrated before [21], with Austria dominated by OA and BM, whereas in Czechia, Poland, and Slovakia, AC. However, there is an increasing trend towards the use of organic treatment in these three countries. For the first time, we showed that analysis can also consider seasonal timing of treatments and operation size, which better reflects varroosis control. Based on our results, the use of BM and OA as implementations of IPM for each beekeeping group is recommended. The benefits of these methods are not only that there is no risk of chemical residues in the bee

products, but also that they can positively affect apiary income [51] and are flexible for all apiaries, even organic ones [52]. We emphasize the need for broad education about varroosis control, as we showed that the most applied treatments do not overlap with efficient pest control. Widespread *V. destructor* resistance to the most commonly used acaricides is a possible catastrophe for all European beekeepers. Given the sensitivity of an emerging parasite threat to European beekeeping to OA and BM [53,54], organic treatment is the answer to effective parasite control. Overall, the results support the promotion of IPM principles, combining chemical and non-chemical approaches, emphasizing treatment timing, and improving education among small- and medium-scale beekeepers.

Conclusion

This study demonstrates that winter colony losses in Central Europe can be substantially reduced through the application of tailored treatment strategies against *V. destructor*. Using decision tree analysis, we identified the BTS for SB, MB, LB in Austria, Czechia, Poland, and Slovakia. While no universal solution emerged, all successful strategies involved the timely and often combined use of BM, OA, and AC. Notably, all BTS resulted in significantly lower winter losses compared to the initial baseline, with reductions reaching up to 19 percentage points in some beekeeper groups. The lowest losses were consistently observed among LB, emphasizing the influence of experience, structured management, and consistent implementation of effective treatment. Despite regional and operational differences, the findings underscore the importance of seasonally appropriate treatments, the avoidance of ineffective or poorly timed applications (e.g., OA in summer within capped brood), and the growing potential of biotechnical methods within IPM. Beekeepers should regularly monitor mite levels and apply treatments strategically based on infestation thresholds.

Promoting data-driven decision-making and increasing access to education and advisory services, especially for small-scale and hobbyist beekeepers, will be critical for sustainable *V. destructor* control and improved colony survival in the future.

Abbreviations:

ABPV, Acute bee paralysis virus; AC, Acaricides; AM, Another methods; BM, Biotechnical method; EMA, European Medicines Agency; EO, Essential oils; COLOSS, Prevention of Honey bee Colony losses (research association); DWV, Deformed wing virus; GDPR, General Data Protection Regulation; GIS, Geographic Information System; IPM, Integrated Pest Management; LB, Large-scale beekeepers; MB, Medium-scale beekeepers; OA, Organic acids; Parasitic Mite Syndrome, PMS; SB, Small-scale beekeepers;

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Table 1. Categorization of *Varroa destructor* treatment methods. This table presents how various reported Varroa treatment methods were merged into five distinct categories (Biotechnical methods - BM, Organic acids - OA, Essential oils - EO,

Acaricides - AC, and Another methods - AM) for analysis in this study. Each category lists the specific active substances or products of treatment it encompasses.

Table 2. Relative frequency of beekeepers who used individual treatments in individual seasons and individual countries. The values above the average for a given season are highlighted in red, while those below the average are highlighted in blue. Only the significant deviations from the average are highlighted. The p-values of tests are as follows: * $p \leq 0.001$; ** $0.001 < p \leq 0.01$; *** $0.01 < p \leq 0.05$

Table 3. Best Treatment Strategies (BTS) for *Varroa destructor* control and associated winter colony losses across countries and beekeeper clusters. The table includes treatment methods only in seasons included in the BTS paths. Red ticks (✔) indicate using of the method in a particular season; blue crosses (✖) indicate not using of the method in a particular season; [a] number of colonies treated by BTS divided by all colonies in each cluster (%).

Fig. 1. Distribution of beekeepers and honey bee colonies across different beekeeping scales in Central European countries; A) illustrates the percentage of beekeepers within each cluster, while B) shows the corresponding percentage of colonies managed within these clusters for each country investigated. Clusters are defined as: small-scale beekeeping (SB), medium-scale beekeeping (MB), and large-scale beekeeping (LB).

Fig. 2. Spatial distribution of honey bee colony density and winter colony loss rates in central Europe (2020 and 2021). These maps visualize the number of colonies and the corresponding winter colony losses (%) across Austria, Czechia, Poland, and Slovakia for two consecutive seasons. Colony losses are represented by color intensity, while the size of each hexagonal grid cell indicates the number of colonies within that 500 km² area.

Fig. 3. Decision trees for best treatment strategies (*Varroa destructor*) and corresponding winter colony loss rates for different beekeeper clusters in Austria. Each tree illustrates the optimal sequences and combinations of treatment methods (Biotechnical methods (BM), Organic acids (OA), Acaricides (AC), Essential oils (EO), Other methods (AM)) leading to the lowest winter colony loss rates for small- (SB), medium- (MB), and large-scale (LB) beekeepers. Paths highlighted by green nodes (leaves) indicate the best strategies with their corresponding percentage loss rates.

Fig. 4. Decision trees for best treatment strategies (*Varroa destructor*) and corresponding winter colony loss rates for different beekeeper clusters in Czechia. Each tree illustrates the optimal sequences and combinations of treatment methods (Biotechnical methods (BM), Organic acids (OA), Acaricides (AC), Essential oils (EO), Other methods (AM)) leading to the lowest winter colony loss rates for small- (SB), medium- (MB), and large-scale (LB) beekeepers. Paths highlighted by green nodes (leaves) indicate the best strategies with their corresponding percentage loss rates.

Fig. 5. Decision trees for best treatment strategies (*Varroa destructor*) and corresponding winter colony loss rates for different beekeeper clusters in Poland. Each tree illustrates the optimal sequences and combinations of treatment methods (Biotechnical methods (BM), Organic acids (OA), Acaricides (AC), Essential oils (EO), Other methods (AM)) leading to the lowest winter colony loss rates for small- (SB), medium- (MB), and large-scale (LB) beekeepers. Paths highlighted by green nodes (leaves) indicate the best strategies with their corresponding percentage loss rates.

Fig. 6: Decision trees for best treatment strategies (*Varroa destructor*) and corresponding winter colony loss rates for different beekeeper clusters in Slovakia. Each tree illustrates the optimal sequences and combinations of treatment methods (Biotechnical methods (BM), Organic acids (OA), Acaricides (AC), Essential oils (EO), Other methods (AM)) leading to the lowest winter colony loss rates for small- (SB), medium- (MB), and large-scale (LB) beekeepers. Paths highlighted by green nodes (leaves) indicate the best strategies with their corresponding percentage loss rates.

APPENDIX 9

Design of decision support tools for the quality assessment of illegal dumping notifications based on crowd-sourced data

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Design of decision support tools for the quality assessment of illegal dumping notifications based on crowd-sourced data

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Abstract: Illegal dumping has become an increasingly significant environmental problem throughout the Czech Republic and also in Prague. The waste is disposed in areas such as vacant lots, along roadways, alleys, city and county parks, ravines, construction sites. The challenge for cities dealing with illegal dumping is that it is tough to identify when it will happen, where it will occur, and how much will be dumped. The paper is therefore focused on designing a decision support tool, which uses crowdsourcing data to cope with this problem as the management of illegal dumps can be built upon citizen reports via the internet. Many people possess smartphones with data connection to the Internet and are not only limited to Wi-Fi networks. Cellular data transfer is one of the most important prerequisites for the usage of mobile applications which are a huge source of spatial data based on crowdsourcing principles. As the quality of reports in time varies, it is important to focus on the spatial accuracy of reports to increase the efficiency of reporting. For this reason, the spatial quality assessment approach is applied in the application for illegal dumping notifications – "ZmapujTo" for the city of Prague. The model uses the maximum entropy approach combined with several other methods for data validation to automatically access the quality of report based on spatial location.

***Keywords**:* crowdsourcing, Maxent, illegal dump, ZmapujTo

1 INTRODUCTION

Illegal dumping means waste dumping into places, which are not meant for it. These places are mostly readily accessible, and there is a small risk that someone will be seen while dumping illegally. Illegal dumping also covers placing waste in the vicinity of other kinds of dustbins that are not meant for it.

Issues of illegal dumping in Czech waste management have been discussed for many years. The essential reason for the discussion is problematic. In most cases is almost impossible to identify the subject which has established such illegal dump. The subject can be sanctioned for the establishment of such an illegal dump as illegal dumping is an offense. A physical person can be fined from CZK 3 000 up to CZK 50 000. Businesses can be fined up to CZK 10 million. Fines for illegal disposal of waste differs according to the originator.

The current legal situation, Act 185/2001 Coll. on waste and change of other acts, as amended by later regulations, does not fully regulate this problem and regrettably means for a much less effective solution of the removal of illegal dumps than previous legal regulation, Act 125/1997 Coll. on waste. This law, apart from the actually legally binding and effective law, addressed the question of illegal dumps particularly in such a way, that responsibility for an illegally gathered dump on certain land is transferred to the landowner.

Certain hope in a stated field can be seen in the newly prepared act on waste, which returns to the original idea of Act 125/1997 Coll. The law enables municipalities with extended obligations to retain more authority to dispose of illegal dumps and also binds the landowner to take proper care of his/her property. From the point of view of the removal of illegal dumps, one of the possibilities is to use crowdsourcing for the notification of illegal dumps.

1.1 Crowdsourcing

Crowdsourcing is formed from two words: crowd and outsourcing. Crowdsourcing means to hire the crowd to solve a certain problem caused by a crowd, mostly by a bigger group of people, usually over the internet and anonymously (Howe, 2008). The crowdsourcing method utilises efficient communication, interest, and drives the community to create content. The community can compete with professionals mostly through the cost of ownership. The task itself is commissioned to the community, not other organisations or businesses. Advantages of crowdsourcing when collecting spatial data rest in the high volume of newly created spatial data for minimal costs. The reason for this is the cooperation of a higher number of persons than an organisation could afford. One of the main disadvantages of crowdsourcing is the complicated assessment of data quality. Information retrieval is a common part of human society. Mobile devices can be used as a means for fast, cheap, and efficient data retrieval. There is a large number of applications functioning on this principle. The most famous are OpenStreetMap, Waze, SyriaTracker, or Flickr.

1.2 Data quality and crowdsourcing

Data quality is a key subdiscipline of geoinformatics. Data quality is determined not only by basic data, but mostly by the user itself. High-quality data can be marked as "accurate and trustworthy". Nevertheless, this definition and the whole subdiscipline faces an inconsistency of used definitions and inaccurate terminology. Information on the quality of observed data is necessary for their selection and proper use. The aim of data suppliers is primarily their repeated use. For the fulfilment of these conditions, it is necessary to follow users' demands during production or spatial data transformation. The second aspect is identical with documentation supplied to the data users (Brus, 2013). From the point of view of crowdsourcing data quality, there is a very thin line between useful and unusable data. Regular data are standardised as a part of the process. For crowdsourced data, it is very difficult to assess geodata quality without a prior standardisation process. There is a large number of standards for geospatial data. These standards should be implemented within crowdsourcing data creation.

Hans-Jörg Stark from the Centre of Geoinformatics in Salzburg states that the ISO 19100 norm series is suitable for the assessment of the quality of crowdsourcing data (Stark, 2010). These norms were created under ISO/TC 211 and developed standards for the use and search for geographical information. It not only addresses technical and semantical issues, but also metadata which is critical for the assessment of data quality. In some cases, there is no need for high-quality data. Emergency situation mapping can be set as an example (earthquake, floods, fires), where a large number of contributions must be processed at the expense of accuracy. Opposed to companies busying themselves with map making, projects based on crowdsourcing are limited by the cooperation of people within the community (Stark, 2010). Some applications were open for users and were prone to error and vandalism. Certain measures can contribute to higher quality of contributions. A request for user login for editing the main elements can be stated as an example. This "limitation" can lead to an opposite effect; it can lower the number of contributors. Overall, data quality assessment is performed with a lower interest of an expert company.

Jeffrey Heer and Michael Bostock from the Stanford University published a study in 2010 (Heer and Bostock, 2010), where they pointed out that data quality of regular spatial data is well solved. For crowdsourcing data, the situation is different since the data are based on voluntary activity. No one is

responsible for metadata creation. These metadata are usually missing, so a check is necessary. This is an irreplaceable prerequisite for a further analysis and usage of data. One of the possible solutions on how to fill the gap between the usability of data and demanding control of quality is the use of a graphical view of data quality, a so-called visual. The principle is to graphically visualise factors that affect the quality of spatial data.

Matthew T. Rice (Rice et al., 2012) from George Mason University in 2012 published “Crowdsourced Geospatial Data”. Many application users using crowdsourcing are not educated in geographics or geoinformatics. These are denoted as "non-geographers". Non-geographers contribute to the community by mining geospatial data, application development, and other media activities. The usage of geographical techniques and tools for personal and community activities or by a non-expert group of users led to the creation of so-called VGI (Volunteered Geographic Information) as a part of UGC (User Generated Geographic Content). According to the author, the biggest advantage of crowdsourcing is in fast data creation, which he proves on many disasters (earthquakes, floods, fires). Michael F. Goodchild (Sui et al., 2013) addressed the quality of crowdsourced spatial data. He has addressed traditional assessment for several decades. According to him, the most important general tool for assessing spatial data quality are metadata and the maximum utilisation of their potential. According to the author, quality data creation is ensured by the large community of contributors. This is the underlying assumption for the long-term lifetime of projects such as OpenStreetMap. Large companies such as OSM or Wikipedia have developed analytical tools for the detection of malicious contributions. The informed public begins to recognise this type of geodata in a full range. Still, questions are asked about how reliable or trustworthy a given data source is. Jingfeng Xia (Xia, 2012) from the University of Indianapolis describes two basic attitudes in quality assessment. These are quantitative metrics based on objective measurement and qualitative metrics based on subjective measurement. The optimum solution is the connection of both attitudes into a so-called multi-level assessment. M. van Exel (Exel et al., 2010) established research of spatial data quality for the assessment of three core indicators. These are the spatial activity of the community (number of editions in a given place), temporal activity (number of editions in a particular time span), and relative activity of the crowd (number of editions when compared to neighbouring areas). However, for this attitude it is necessary to possess historical information from crowdsourced data..

For working with crowdsourcing data is important to develop a conceptual model for crowdsourcing data quality assessment (Idris et al., 2014). Authors described a method of creating an automated search and comparing processes for their accuracy and subsequent validation. The description of the automated tool is included. This tool uses the conceptual model itself. Authors from from Stanford University have introduced an approach for ensuring quality data using a search, where the margin of error, or inaccuracy during mapping, respectively, is greatly reduced (Sarma et al., 2014). Generalised algorithms for use in some case studies are included. These algorithms are applied to real data. The authors assert that there can be cases of creation and utilisation of crowdsourced data, where maximum spatial accuracy is not required. In this case, the algorithms will be inefficient for use in GIS.

1.3 Application for illegal dumping notifications – ZmapujTo

The first version of ZmapujTo.cz was formed in 2012 as an ecological project for the fight against illegal waste dumping in the Czech Republic and also as a contribution to the solution of the issue of illegal dumping (Kubásek, 2015; Kubásek and Hřebíček, 2013). The project was focused mainly on citizens that do not like the illegal dumping in their towns, municipalities, or the countryside and want to do something about it. Knowing the current situation was the first step. At the time of creation, there was only a database of old ecological burdens, which covered the illegal dumps only marginally. In order to cover the largest possible area and utilise the potential of crowdsourced data, a platform was founded for information gathering from citizens. The modern, efficient, and widely-accepted platform had to be chosen for mapping while using the mobile application and interactive web form for reporting. The first version of the application was very user-friendly and, thanks to the mobile application, any smartphone user could very quickly and easily report illegal dumping. In case the user did not own a smartphone, he/she could report an illegal dump using an interactive web form. More

than 2 500 illegal dumps were reported, and more than 40 municipalities and towns took part during the lifetime of the first version. In March 2014, the second version of ZmapujTo.cz was launched. This version introduced several new features. The goal of the project, to fight illegal waste dumping in the Czech Republic and to make citizens act, remained the same. The most important change was the ability not only to report illegal dumping, but also a variety of other problems that someone can encounter both in town and in the countryside. The entire website was redesigned, including an interactive map for efficient, fast, and intuitive work. Thanks to its responsive design, www.ZmapujTo.cz can be used directly from a tablet or a phone.

1.4 Used technologies

Single regions are sorted in the application according to the ArcČR 500 geodatabase (version 3.1) which is available for free. For reports, Google Maps API is used. Google Street View is also implemented in the application. Therefore, users can scout the given location which makes orientation easy. The Land Register is also available for the detailed preview of the report. The website's responsive web design is based on the Twitter Bootstrap template and is programmed using the AngularJS library as a single-page application with a connection to Google Maps API. The backend server runs on NodeJS (event-managed runtime based on JavaScript) and Express (application framework over NodeJS). For data storage, the document-oriented NoSQL MongoDB database is used. Mobile applications are based on Sencha Touch and Apache Cordova technologies, whose API is built on PHP using Symfony framework, Doctrine ODM. The Mandrill platform is used for sending e-mail notifications.

2 SYSTEM FOR SPATIAL ASSESSMENT OF QUALITY OF INDIVIDUAL REPORTING

The practical part of quality assurance of single reports was created for the capital region of Prague. This area was chosen deliberately as the sequel to the data set supplied in the form of open data by the Planning and Development Institute of Prague. Open data are information and data that can be used without limitations and are available for free. The data are available under CC BY-NC-ND 3.0 CZ (Creative Commons Attribution – Non-Commercial No Derivatives 3.0 Czech Republic license). The license allows copying and further distribution on any media in any format. The condition is keeping the same license. Data published in this way enable further research, analyses, but also commercial use for the creation of internet applications. The Planning and Development Institute of Prague (IPR Praha) is offering geographical data in the form of open data formats and web services. Open data are published in vector formats such as Esri shapefile, geo JSON, GML, DXF, or bitmap TIFF and JPG formats. Apart from bitmap data, open data are published in S-JTSK and WGS-84 coordinate formats. The advantages are similar metadata records. The following data layers were used for the implementation of quality assessment:

- Current land use – WGS 84, 1:5 000,
- Planned land use - (regional plan) – WGS 84, 1:10 000,
- Prague orthophoto – S-JTSK , (pixel 10 cm),
- Bridges 3D – S-JTSK.

Spatial data of the street network of Prague are retrieved from the Register of Territorial Identification, Addresses, and Real Estate (RUIAN). These data are used for optimising the result.

Actual data from the ZmapujTo application are used as a database of illegal dumps. Data are supplied as "Open Data" under license CC BY-NC-SA 4.0 (Creative Commons – Attribution – Non-Commercial-

ShareAlike 4.0 International). The data format is GeoJSON. Data are updated for download with one-day delay from "datacube.io".

2.1 Methods and procedures

In places where illegal dumps were not reported and for the computation of illegal dump probability distribution in places, the maximum entropy - Maxent algorithm for was used. This algorithm was used for modelling the spatial distribution of organisms. The name “Maxent” comes from maximum entropy, i.e. maximum entropy or level of organisation. This model is described by S. Phillips (Merow et al., 2013; Phillips and Dudík, 2008). It is a statistical method, which uses present data. Therefore, all data have to be prepared for use in this modelling software. Data points of illegal dumps in GeoJSON were converted into an Esri shapefile. Input data were selected based on set conditions: a) only illegal dumps, b) middle and large sizes. To make sure that the data were correct and dumps were real dumps and of the correct size, a manual check using photographs was conducted. 686 illegal dumps in the area of Prague were the results of the visual analysis. During another part of the preparation, the SDMtoolbox was used (Brown, 2015). For the removal of data duplicity and influence of neighbouring results, data selection was applied based on spatial autocorrelation with a value of 50 meters. The input layer for analysis finally contained 318 dumps. In the second, data had to be prepared as environmental layers. Spatial data from IPR Praha were processed. Detailed metadata records are available for these data on Prague’s geoportal. For data preparation to be accepted by Maxent, the python based toolbox “PrepareDataforMaxent10_1” toolbox (Dilts, 2015) was used. Attribute records were altered for the subsequent bitmap. Vector data were converted into a bitmap format – the size of one pixel was set to 1x1 meter. Maxent modelling software was used for the single type of occurrence modelling based on environmental variables. A dataset representing places of real occurrence of illegal dumps over 50kg in the area of Prague in the CSV format was used as a first input. ASCII files of the actual situation of land use and functional areas prepared in advance were used as “environmental layers”. The resulting model represents a regular square grid, where every cell (square) represents probability of occurrence of illegal dumps. The resulting bitmap was visually checked using an orthophoto. By manual check, the resulting bitmap was optimised. A layer of current land use was used for optimisation. According to the "KOD" attribute, 66 types of land use with minimum probability of occurrence of illegal dumps were selected by expert estimation (structures, education facilities, etc.). The chosen probability of occurrence of a dump for a given functional area was subsequently integrated into the resulting layer with the goal to lower the probability within this functional area. A solution to possible spatial error when using GPS localisation in the mobile device by setting a possible error to 10m was implemented into the computation at the same time. Infrastructure was optimised after repeated checks of the functional area. This list of infrastructure was gained from RUIAN and converted into the geodatabase. Important structures and streets were exported from the vector layer of the actual situation of land use. Using the “Select by locations” function, infrastructure was used and exported into the new layer. For this infrastructure, a surrounding zone (buffer=3 meters) was computed and the optimisation procedure was repeated in the same way as in the first case. For regular streets, the buffer was set to 2 meters. To ensure the correctness and filtering out the possibilities of "inaccurate" placement of illegal dumps, an optimised bitmap was "smoothed out" using a "Focal statistics" filter (neighbourhood=circle) and radius (cell=10) were set for the computation.

2.2 Results

A raster of probability of illegal dumps in the area of Prague is the result of the whole process of preparation, computation, and optimisation. This result will be used for checking the probability of correctness of citizens' reports since the checks are currently carried out solely manually. For optimisation purposes, the raster was checked from the point of view of prediction accuracy of illegal dumps. In the first place, 52 randomly selected and placed points in the area of Prague were checked. The check was carried out manually over orthophotos by expert estimation. This expert estimation was subsequently observed with values taken over from the optimised raster. The result concluded that 48 points were real and four were misplaced – showing 92% accuracy. In this case, a 13% increase in accuracy in comparison with the non-optimised raster.

In another stage, real data from the ZmapujTo application were used. 314 illegal dumps in Prague were used. These dumps were checked that they really exist or existed in the given places. In this case, there is an expectation that all dumps should be located in places with a higher occurrence probability than the expertly set threshold of 30%. Thirty percent is an expertly set threshold value expressing the probability threshold, where there is a real expectation that an illegal dump really exists. At the same time, it is possible to get the value of the probability of occurrence of an illegal dump at a given place. Direct implementation of the resulting model into the ZmapujTo application is possible in the future. Currently, individual reports are checked manually (Figure 1).

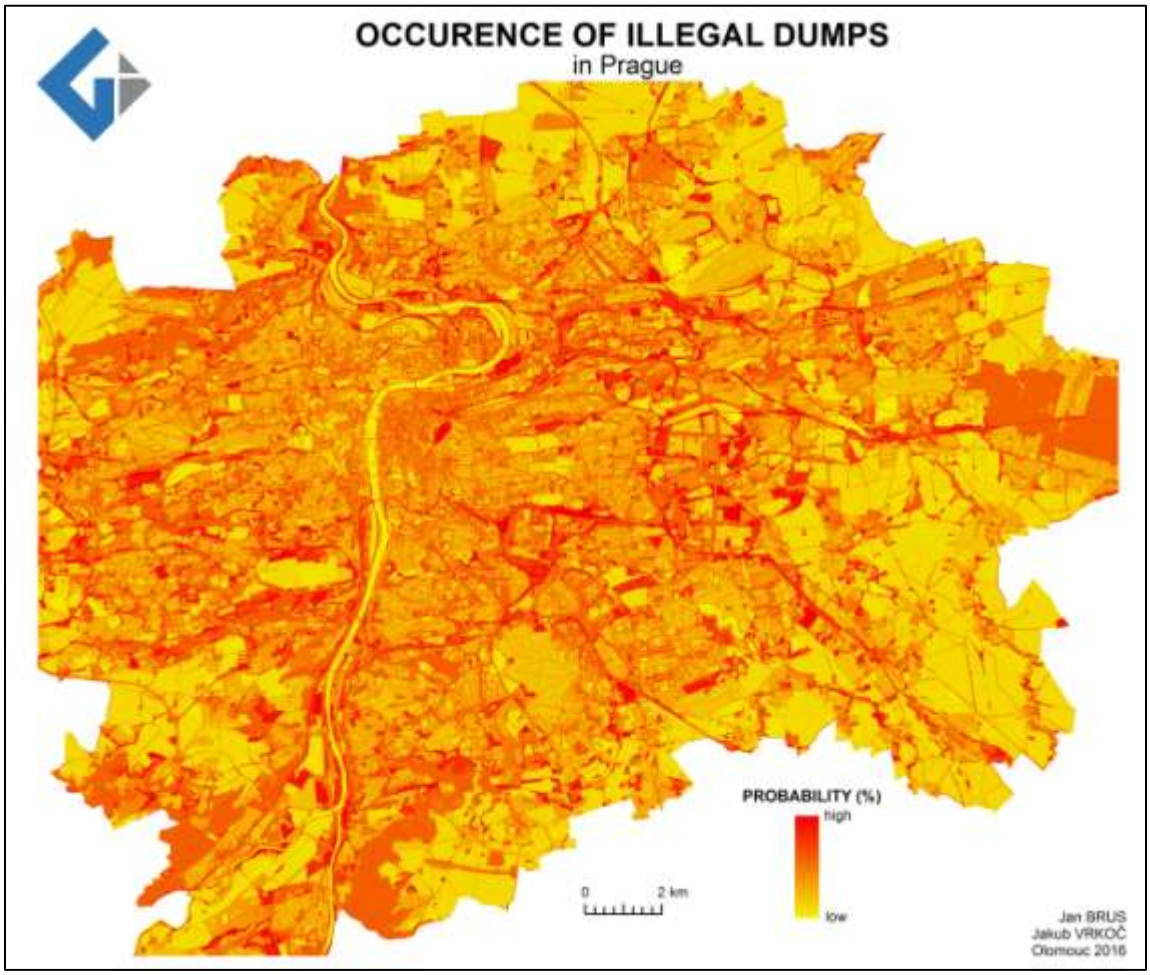


Figure 1: Probability of illegal dumps in Prague

3 DISCUSSION

The resulting model will be the basis for the development of a semiautomatic tool, directly connected with the ZmapujTo application allowing for the processing of reports. Processing would include the investigation of the probability that a given dump can or cannot occur in a given area. For data control, some threshold would be set. In the case that the probability of occurrence is lower than the set value, then manual administration would be triggered. In the other case, a report would be automatically forwarded to an appropriate municipal or city department that is responsible for the agenda of illegal dumps. It is necessary to note that this tool would solve only spatial accuracy, meaning if it is possible that an illegal dump is occurring in the given place or not. Disadvantages of automatic forwarding occur when an attribute accuracy check would take place. These attributes involve situations when people report only a minor mess or overfilled dustbin as an illegal dump. At the same time, the existing concept faces the problem of accurate localisation of the dump.
Especially in dense urban areas and forested areas, accurate localisation using a smartphone is highly problematic. Location can be determined with a +- 10 meter inaccuracy as illegal dumps can be placed in the middle of a road, in a stream, or the centre of a building. The resulting model tries to eliminate spatial error using a focal circle filter with a 10m diameter.

Nevertheless, placement inside a building or house does not necessarily mean an error in the data. In the case that the mobile phone does not enable connection using data packets, the ZmapujTo application enables a person to record the report in the phone's memory and send it later using a Wi-Fi connection. This may cause that the location of submitting the report will be recorded. This error can be eliminated by manual localisation directly on the map, also enabled by the application. Computation of probability of occurrence of illegal dumps for big cities in the Czech Republic as well as for the entire Czech Republic would be highly problematic. Not all cities share the same attitude towards data as Prague. A high computational demand presents another issue. A stand-alone model of occurrence of illegal dumps can be useful for particular quarters of Prague; for the detection of places where a higher risk of occurrence of an illegal dump exists.

4 CONCLUSION

Crowdsourcing has rapidly developed due to an increasing number of people with access to the internet. Many people possess smartphones with a data connection to the internet, not only limited to Wi-Fi networks. This is one of the most important prerequisites for the development of mobile applications, which are a huge source of spatial data based on crowdsourcing principles. A system for the assessment of spatial accuracy is only one part of a complex tool for reporting quality assessment accepted by the ZmapujTo application. Another integral part is the concept of assessing attribute accuracy. Assignment of the correct category to the report is crucial (such as illegal dump, minor mess). In the case of illegal dumps, the application allows a person to enter the weight: Less than 10kg - small, less than 50kg - medium, large. This assessment is very subjective - weight estimation can be problematic for users. Due to the given reasons, a decision scheme for the correct classification will become part of the final application. In the case of applying the system to real situations, there is an expectation that 90% of large illegal dumps will be automatically assessed and handed over to authorities. This will save administrators time because, until now, all reports were assessed manually.

The Planning and Development Institute of Prague is also interested in the outputs. Maps can also serve for occurrence prediction. The Planning and Development Institute of Prague can then detect places where illegal dumps occur more frequently compared to other areas of Prague.

Apart from major applications such as OSM, which use quality assessment based on complex algorithms, this method is strictly based on solutions using the GIS approach. Using GIS for these types of tasks is not very common, therefore, the goal of this paper is to introduce possibilities how to successfully use GIS in the given field. This tool is a typical case of use of simpler analytical tools for the creation of complex tools for the assessment of spatial data quality. Successful connection of crowdsourcing and GIS opens new areas of geoinformatics. Geoinformatics possess significant potential for future utilisation in the given domain.

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APPENDIX 10

Efficient Interactive Tactile Maps: A Semi-Automated Workflow Using the TouchIt3D Technology and OpenStreetMap Data

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Article

Efficient Interactive Tactile Maps: A Semi-Automated Workflow Using the TouchIt3D Technology and OpenStreetMap Data

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Abstract: Despite the growing efficiency of the map-design process in general, tactile mapping has remained peripheral to mainstream cartography. For a specific group of people with visual impairment, however, tactile maps are the only effective way to obtain a complex idea about the geospatial distribution of the surrounding world. As there are numerous specifics in creating these 3D maps and only a limited group of users, tactile products have usually been either very simple creations or, on the other hand, difficult and expensive to produce. Modern trends and progress in the availability of new technologies (e.g., 3D printing) bring new possibilities for keeping tactile map production both effective and up to date. Therefore, this paper aims to present a methodology to apply the TouchIt3D technology to link 3D-printed multi-material tactile maps with a mobile device. Utilizing this solution resulted in a set of interactive tactile maps following current trends of inclusive education. Using OpenStreetMap data together with a semi-automated workflow significantly lowered expenses compared to antecedent maps with similar functionality. A semi-automated workflow was designed, focusing on three use cases of independent movement: walking, using public transport, and tourism.

Keywords: tactile maps; interactive maps; multimedia maps; visual impairment; user adaptation; OpenStreetMap; 3D printing; TouchIt3D technology

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1. Introduction

A huge diversity of modern people's needs and aims is reflected in the field of map-making. Cartographers create a huge range of maps targeted to masses of people, but there is also a need to design maps narrowly focused on specific user groups. People with severe visual impairment representing an important group of users use tactile maps providing at least a simple scheme of how the world around is structured. Tactile maps also play an important role in the educational process at schools [1]. The most important of the education of people with visual impairment is the proper perception of the spatial characteristics enabling them to learn independent movement [2]. Nevertheless, it is not commercially attractive to design special maps for this target user group.

Tactile maps differ from other maps in several aspects. First, these maps need to be greatly simplified so that the map complexity is at a low level and map symbols are easily interpretable by touch [3]. This requires a high level of generalization applied to source data to avoid a complexity present in many current maps [4]. Furthermore, tactile maps intended for independent movement are usually of a large scale. This brings the need for mapping very detailed guidance elements (such as obstacles on sidewalks, pedestrian crossings etc.), which are usually not present in most geodata sources. Unlike with a 2D map, when creating a tactile map, it is necessary to think about height levels and sufficient differences between them so that they are decodable by user's fingers. Therefore, some tactile maps are designed directly in the form of a 3D model while others are drawn in 2D, with a relief surface manufactured later during the production process [5].

Due to difficulties related to the creation of tactile maps, both the design process and the manufacturing process for each map are time-intensive for cartographers. Especially in the case of 3D printing, several printing parameters need to be set, and the actual fabrication may take several more hours. Those factors result in high costs of tactile maps, both financial and time-wise. Even more expenses come with multimedia tactile maps. Kohn [6] describes how electronics, multimedia content, and implementation of both hardware and software into the tactile map body can easily double the costs.

TouchIt3D technology linking 3D-printed multi-material tactile maps with a mobile device was developed in order to make tactile maps attractive, affordable and useful. This solution, described in detail in Section 3, together with a semi-automated workflow were applied to provide affordable maps which can help people with visual impairment explore the world around them. With the use of modern technologies and the benefit of significantly lower costs, new interactive tactile maps were designed and examined in user testing.

Related Works. As described by Jesensky [7], real-world objects are represented by tactile map symbols in tactile maps. Those relief forms of point, line and area symbols may include parameters such as vertical dimension, roughness, and 3D texture [3]. Simple tactile maps commonly occur in public locations and buildings in developed countries. Additionally, places with dense pedestrian traffic and concentration of people with visual impairment are often more likely to be equipped with audio systems and tactile maps. These schemes of a limited area may illustrate crossroads, landmarks, or the floorplan of a building. They are either created for people with a visual impairment only or combining both visual and tactile elements (Figure 1).

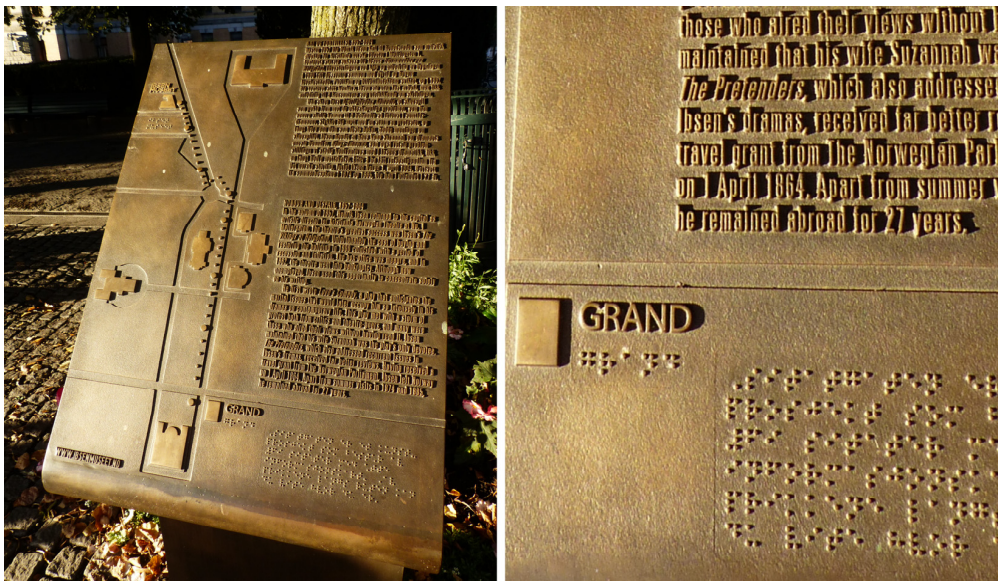


Figure 1. Information board containing a tactile map with a description in both Latin script and Braille (source: authors).

Captions and descriptions are typically expressed in Braille [8]. This well-known system, unfortunately, has several limitations related to tactile maps. Newman et al. [9] describe the common size of each letter of 4 × 6 mm, but the standard size varies between countries as well as for different uses [10]. In all cases, Braille symbols need to be larger than non-relief fonts, and so the captions are abbreviated very often. Awareness of the existence of Braille is relatively good, but Braille literacy, even among those with severe visual impairment, is not unequivocal [11]. Still, a large number of visually impaired people do not use Braille and rely on modern technologies, e.g., Text To Speech (TTS) in mobile devices, providing simpler ways of obtaining information.

Consequently, methods other than Braille are often used for the transmission of information. The most common example is acoustic signaling at pedestrian crossings and special audio beacons activated remotely when a person with visual impairment enters the area. In some cases, the devices at the pedestrian crossings are supplemented by a simple tactile map. Figure 2 illustrates one of the pedestrian push-button systems developed by the Swedish company Prisma Teknik present in various models across a number of European cities [12].



Figure 2. A simple tactile map by a pedestrian crossing in the city of Trondheim (source: authors).

There are two basic methods of tactile map creation—either manual or machine-made. One of the oldest and simplest ways of communicating spatial information to people with serious visual impairment is the technique of palm-drawing. This technique is often used by teachers and relatives of the visually impaired, giving at least a temporary stimulus with information indicating spatial distribution. Similarly, hand-made tactile map aids made of various materials are common [13]. Quick-drying dense color gels are another possibility that is widely available in stores.

Advanced methods can be performed using machine techniques, e.g., Braille printers, which are usable for simple tactile maps. Cardboard embossing is also used especially to produce tactile postcards and greeting cards. The height of the raised layer can reach up to several centimeters. The more durable alternative, using the same principle, is forming plastic or metal plates. The production of a mold realized using a laser former is the most expensive part of the entire production process. Thermal printing is a commonly used technology due to its effectiveness and accessibility for creating a relief surface. The dark-colored parts of a microcapsule paper in a fuser swell up and acquire volume to create a positive relief while the rest remains at the original height [14]. During the last decade, 3D printing has become another promising technology for creating terrain visualizations and advanced tactile maps, e.g., [15,16].

Arditi et al. [17] describe the advantages of interactive tactile maps in orientation while moving through interior spaces. This study was an early attempt to design interactive tactile maps linked with a mobile device using thermal printing. In the case study, authors halved the number of failures in finding the correct route with the help of multimedia tactile maps, compared to interviewing passers-by instead.

In recent years, numerous studies have focused on the automatization of tactile map creation. Wabinski et al. [15] reviewed the possibilities of automated preparation of tactile maps and concluded that the most difficult part was the generalization of source data.

Automated processing of image maps into the form of 3D relief using the Scalable Vector Graphics (SVG) format was addressed by Wang et al. [18]. Public geodatabases such as OpenStreetMap (OSM) are often used to automate map creation, even in the case of tactile maps [19]. Götzelmann [20] also presents an application of 3D printing and a partially automated approach for creating tactile maps from an OSM database. The author describes a workflow using simple 3D printers to enhance the autonomy of individuals with visual impairment. Possible customizations of tactile maps are later followed by Taylor et al. [21].

The use of a 3D-printed case with an interface made of conductive parts aimed to operate a mobile device is presented by Zhang et al. [22]. Even though the presented system does not aim to represent tangible map symbols that are not developing spatial awareness, it enables mobile accessibility across multiple existing mobile applications. A similar innovative attempt was performed by Bornschein et al. [23], developing a tool to access 3D graphic software by people with severe visual impairment. The creation of tactile maps using 3D printing was also researched by Rener [24]. The study focused the use of automatically generated tactile maps for mobility using location-based services. Taylor et al. [25] performed another promising research with automatically generated tactile maps. The study presents a platform where the maps can be manufactured even by the people with visual impairment themselves. Some of the maps also use the conductive parts to be linkable with a capacitive touchscreen. Unfortunately, all the presented maps are limited to use only positive relief structures (extruded up from the base plane). Additionally, the idea of multi-material tactile maps being created by blind people themselves seems to be possible just partially, which is also supported by previous experiences.

Gual-Orti et al. [26] focused their attention more on the evaluation of tactile-map symbols. Following the User-Centred Design approach, potential users with various visual impairments performed the experiment to express differences in map symbol shapes of 3D-printed tactile maps. A study on automation of data processing for non-interactive tactile maps made by thermal fusers was introduced by Stampach et al. [27]. This study also stressed the importance of map symbol dimensions to fulfill the target users' needs. The technology applied for map creation, however, unlike 3D printing, uses only 2D input data with no need of 3D modelling. Similar efforts with this technology were presented by Touya et al. [28]. Among academic sources, there are also several websites providing a tool to prepare simple tactile maps of any region of the World either for 3D printing (touch-mapper.org) or for printing on a microcapsule paper (hapticke.mapy.cz/?lang=en). Unfortunately, both the online sources have a very limited functionality and possibilities to change visualization properties. Due to these limitations, it was not possible to apply them in our study.

The process of 3D printing is also being used to create real 3D models of terrain and other continuous surfaces. With accessible web applications, e.g., TouchTerrain (touchterrain.geol.iastate.edu), The Terrainator (terrainator.com), Terrain2STL (jthatch.com/Terrain2STL), downloading terrain model becomes easy even for amateurs. When 3D printed, these models may help people in geospatial orientation and understanding the landscape structure [29], not only to people with severe visual impairment.

2. Materials and Methods

2.1. TouchIt3D Technology

The TouchIt3D technology was developed in 2014 at Palacky University Olomouc, Department of Geoinformatics, to increase the efficiency and extend the functionality of tactile maps. Its principle consists of using a 3D printer with multiple extruders to manufacture plastic maps combining conductive (interactive map symbols) and nonconductive (non-interactive topographic base) materials. The TouchIt3D tactile maps, when laid flat on a capacitive touch display of a smart device (e.g., tablet), are connected via the display, and so the electric touch signal can go from the fingers of map users through the interactive map symbols made of conductive filament and interact with the display. A tablet using a preinstalled Android application provides an audio description that can differ according to

the location of the signal interaction across the display. This combination allows to avoid the need of Braille in maps and to lower the complexity of each map while preserving the information amount that each map symbol represents.

Within the TouchIt3D technology, a tablet or another mobile device with a capacitive touch screen serves as a universal carrier of electronic equipment, enabling audio-visual and tactile information to be transferred to the user as a reaction to a finger contact (Figure 3). It can be used for an unlimited number of different tactile maps or other landscape models. This approach advances the older-style interactive tactile maps, each of which contained its own electronic installation. The mobile device is also equipped with an elementary set of sensors (GPS, compass, accelerometer, etc.) and the possibility of connecting to the Internet via WiFi or mobile data. The exploitation of these sources is expected to be examined in further research. However, in this paper, no position sensors nor internet connectivity were used for tactile maps aiming especially for offline use. Nevertheless, a mobile application is a necessary component of TouchIt3D technology. It was developed for the Android operating system defining a set of buttons positioned according to the positions of each tactile map's conductive elements. Predefined texts for individual buttons have been converted via a Text To Speech (TTS) function into a voice describing properties of POIs.

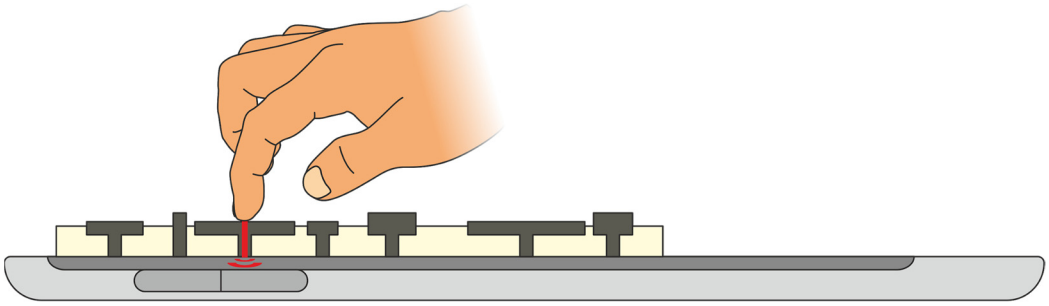


Figure 3. TouchIt3D technology principle when touching an interactive map symbol.

Tactile maps were linked with the tablet using rubber bands encircling the tablet from its bottom side and attached to hooks on both sides of the tactile map (Figure 4). After launching the application, the user may choose the appropriate scheme (button distribution), add a new one from a JSON file, and delete schemes already loaded. After choosing a scheme and mounting the map, when an interactive map symbol is touched, the signal passes through the conductive element to the touch screen of the device, and an audio description is played (Figure 3).

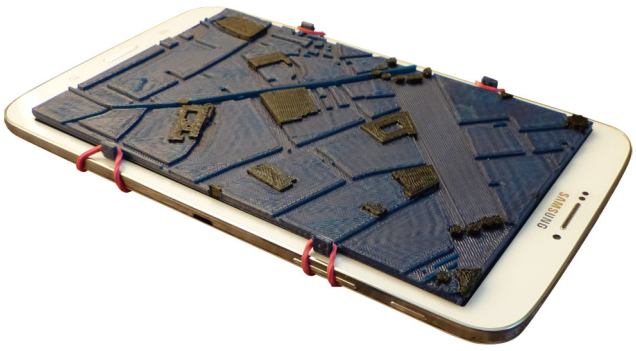


Figure 4. A tactile map attached to a tablet using rubber bands (interactive map symbols in black).

A low-cost 3D printer, the Poseidon Duo (priced around €500), was used for tactile map manufacture. This printer utilizes Fused Filament Fabrication (FFF) technology with two extruders. Using both nozzles allows the individual parts of the tactile map to be made of two different materials. Map symbols representing points of interest (POI) intended to be

interactive were printed of the electrically conductive Proto-Pasta PLA material. Ordinary PLA (polylactic acid) filament was used for the fabrication of the topographic base and the rest of the tactile map body. It was necessary to create a separate virtual 3D model for each of the two tactile map parts, as described in detail in Section 2.3. Conductive map symbols were stretched across the entire height of a tactile map from its lowest to the highest edge. The calibration of the proper height of the nozzles above the printing bed required the utmost attention during the preparation phase of the 3D printing process, as this step influences the quality and functionality of TouchIt3D maps.

2.2. User Preferences Survey

In order to determine appropriate map content, the ideas of testers with visual impairment were taken into account alongside our team's previous experience with tactile map design. All consultations with people with visual impairment realized during the research were interview-based and focused on intensive and deep analyses of the issue rather than collecting flat data from a large set of anonymous people. Therefore, initial user input was collected to decide objects usable for people with visual impairment. Seven blind people aged 23 to 58 years joined the preliminary evaluation one after another. Additionally, one employee of an institution for the education of the visually impaired was interviewed, describing his knowledge of simple tactile map design and user issues. Meetings with all the users took place in familiar and calm locations in the city of Olomouc, Czechia.

Three sample tactile maps capturing a limited area of the Prague city center scaled 1:3000 to 1:5000 (one of them shown in Figure 4) were used to demonstrate the map functionality and concept. Those maps were prepared manually using OSM data in the geographic information system (GIS) and 3D modeling software Blender. Maps contained streets at the lowest height level and blocks of buildings in the next one. The third layer represented tram lines and the highest interactive layer grouped all POIs (public transport stops and buildings important for the public, e.g., restaurants, shopping malls and banks). Additionally, a special star-shaped interactive symbol was added in the top left corner with a description of the map. The description contained what area the map covers, what the scale is, what each layer represents (the map legend) and the date of the map's creation.

During the interview, each respondent was first questioned regarding their previous experiences with tactile maps. Subsequently, the sample maps and their functionality were described and shown. Respondents then had time to explore all three maps differing in the scale (1:3000; 1:4000; 1:5000) and were guided to experience all the different map symbols when needed. Respondents were asked to choose which scale levels were readable for them. In the next stage, each of them was asked to decide which real-world objects from several categories would be important for them to be mapped on this kind of tactile maps. Respondents were also asked which of those POIs would be helpful to be mapped using interactive map symbols with auditory descriptions, and, on the other hand, which POIs would be not. Finally, an unstructured discussion about their feelings regarding the maps, potential uses, suggested improvements, and locations worth mapping was held.

Six respondents of seven stated they had already used some kind of tactile map, but only one person claimed to use them regularly. All the respondents were used to handle with mobile devices like mobile phones and tablets. They were familiar with using various mobile applications and screen-readers using the TTS function, e.g., TalkBack (Android) and VoiceOver (Apple).

All participants positively evaluated the interactivity of map symbols. Minor difficulties with orientation occurred during the initial use of the maps. Respondents usually used both hands to explore the extent of the map. This behavior often launched multiple voice descriptions of the interactive map symbols and was confusing for the respondents as they had no idea which objects were being described at the time. Therefore, it was proposed to modify the audio description to launch only after a longer period holding a map symbol (e.g., 1 s). Scales 1:3000 and 1:4000 were generally considered appropriate and easily recognizable. As expected, the largest scale, 1:3000, was evaluated as the most

easily readable one, but in the case of 1:4000, the larger scope was also appreciated. Except for two respondents, the map scale 1:5000 was evaluated to be difficult to read, as many mistakes related to skipping over (not noticing) some mapped streets occurred. A majority of the respondents also suggested more significant height differentiation of the interactive map symbols compared to the non-interactive background to be sure which objects launch the audio description. All respondents agreed that the best solution for height ordering the layers was according to how they were lined up in the real world.

While there was generally a consensus among the participants on the recommendations mentioned above, answers related to the importance of POIs differed among respondents. Some preferred rather simple maps containing only the elementary landmarks necessary for orientation and movement (e.g., streets, inaccessible areas, and POIs). Conversely, more experienced tactile map readers were interested in more landscape features, e.g., water areas and railways. As described in Figure 5, all visually impaired participants of the preliminary survey marked it as important to show the road network and public transport stops in tactile maps. The majority of them also highlighted the importance of marking medical facilities, banks, and post offices in tactile maps, while the rest of the respondents stated that those POIs can help but were not fundamental. Hotels, restaurants, and offices of state/regional/city authorities were found slightly less important for respondents. Cultural institutions, tourist landmarks, and monuments were mostly evaluated to be helpful but not necessary. None of the respondents marked educational institutions as important POIs to be visualized in the maps.



Figure 5. Map content demands according to the preliminary user preferences survey.

The highest demand for interactivity was noted in the case of medical facilities, restaurants, and hotels (mostly evaluated as highly important). Additionally, the interactive voice description of the street network, banks and post offices was found to be highly important compared to other categories. Map interactivity of tourist landmarks and monuments was mostly evaluated to have low importance, and the "not important at

all to have the auditive description" was the most frequent response for the rest of POIs (Figure 5).

2.3. Map Design Workflow

Based on findings from the user survey described in Section 2.2, a workflow for semi-automated creation of interactive tactile maps advancing the TouchIt3D technology was designed. The workflow includes obtaining geodata, the processing of that data, 3D modeling, the settings of printing parameters, the printing itself, and the preparation of a template for the mobile application. As there are conceptually different steps included, it is hardly imaginable to automate the entire workflow. In addition, some processes must be done specifically for each map and for each different 3D printer. Despite these challenges, several steps representing a consistent sequence of steps have been automated to make the design process more effective. Whole the process was divided into three blocks according to the primary environment of processing—the GIS block (Figure 6), the 3D modeling block, and the 3D printing block (Figure 10). Automated parts are marked in red in the subsequent schemes.

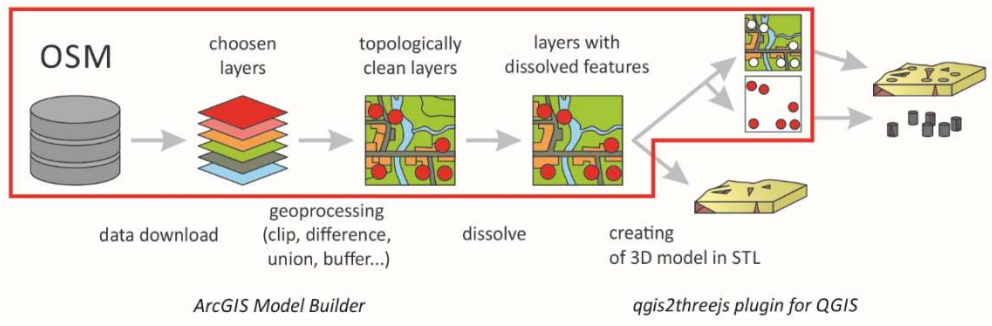


Figure 6. GIS block scheme of the tactile map creation workflow.

The source data for further processing originated in the OSM database covering the whole world, although the quality could differ across regions. Data were imported using the ArcGIS Editor for OSM plugin in ArcGIS for Desktop software [30] and transformed into a UTM Zone 33N projection as the sample areas of interest were located in Czechia (the city of Ostrava and the town of Konice). In the following steps, all point and line features were converted into polygons which could be later extruded into 3D. Therefore, the layers were processed using geoprocessing tools into a topologically clean representation covering the entire area of interest. All of the layers were also cropped for the area of interest defined by a separate polygon layer.

As the preliminary survey (see Section 2.2) showed various aims of potential map users, three different types of tactile maps were designed and visualized using 4 to 5 height layers. The first map type was designed primarily to assist people traveling on foot, the second one for those using public transport, and the third, most detailed map, being designed for tourism purposes. The ArcGIS Model Builder tool (a graphical programming interface of ArcGIS software used for automating processes) was used to automate the processing of the layers differently for each map type. The simplest model is captured in Figure 7 to illustrate the number of steps included in the models. The model mostly used the Selection, Transform, Buffer, Dissolve, Clip, and Union tools to achieve geospatial layers representing individual height levels of tactile maps.

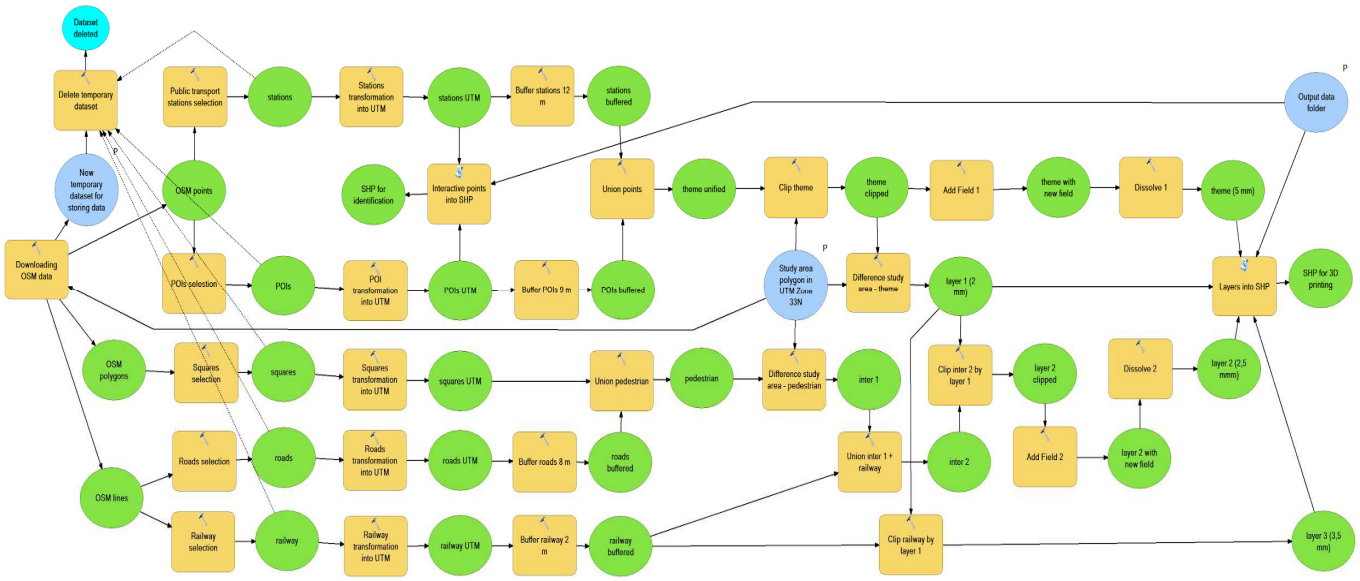


Figure 7. Illustration of the complexity of the data processing scheme for the Public Transport map type (link to the toolbox with all three Model Builder models with readable captions is available in the Supplementary Materials section).

For further steps, the Qgis2threejs plugin along with QGIS [31] software was used as the best solution for exporting GIS layers into a 3D model. This plugin provides, besides other functionality, the conversion of 2D vector layers into an STL file format according to parameters set in its user interface (Figure 8). Layers were extruded to the height 2 to 5 mm, differing among map types (Table 1). The lowest layer representing the street network was identical for all three map types, reaching 2 mm height. Additionally, the height of interactive map symbols was extruded identically, reaching 5 mm height to adopt recommendations from the preliminary survey to be easily distinguishable from the others (Figure 9). The interactive map symbols represented POIs, including public transport stops, shops, hotels, restaurants, banks, and medical services. Other POIs, e.g., educational institutions, were not mapped in order not to overload the map and due to their low attractivity for people with visual impairment.

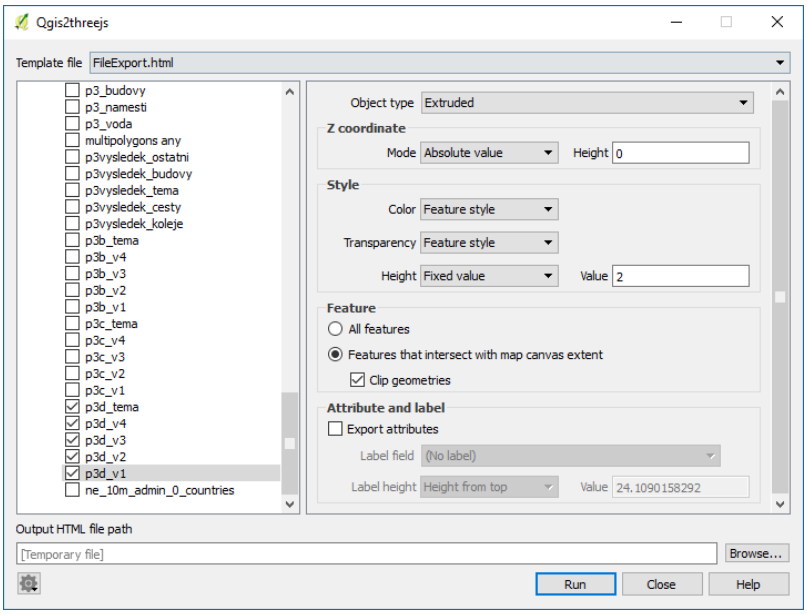


Figure 8. Interface of the Qgis2threejs plugin where individual layers are being chosen in the left menu, and the bottom (Z coordinate/Height) and top (Style/Height) levels are set for extrusion.

Table 1. Height ranges of individual layers for all three map types.

THEME	0–2 mm	2–2.5 mm	2.5–3 mm	2.5/3–3.5 mm	0–5 mm
Public Transport	streets	open spaces and building blocks	---	tram lines	POIs
Walking	streets	open spaces	---	buildings	POIs
Tourism	streets	open spaces	forests, parks	buildings	POIs

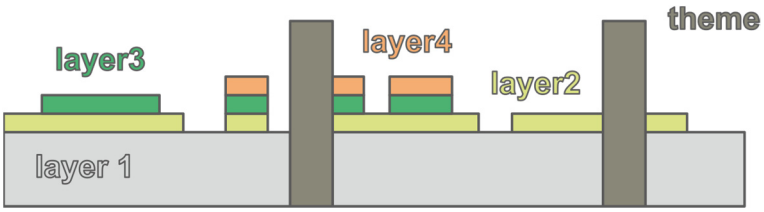


Figure 9. Layer distribution on an example map of Tourism type (layer 1 = streets, layer 2 = open spaces, layer 3 = forest and parks, layer 4 = buildings, theme = thematic layer of POIs).

The Public Transport map type was generally the simplest one, merging buildings with other open spaces without streets or paths. On the other hand, the Tourism map was expected to be the most complex and the most difficult to read, having five height layers instead of four (Table 1). This map was intended for experienced tactile map readers. All the maps were prepared uniformly in 1:4000 scale. The 3D modeling block (Figure 10) begins with automatic repair of potential geometry errors in STL files. In this step, realized in the 3D Builder [32] freeware software. This process is very straight-forward and involves only to agree with the repair. Then, all non-interactive layers were merged, resulting in two 3D models instead of four to five separate models. One model represented the topographic base layers for non-conductive material, while the other represented the thematic layer of interactive POIs prepared for conductive material. Union Boolean operation was applied in the process of merging.

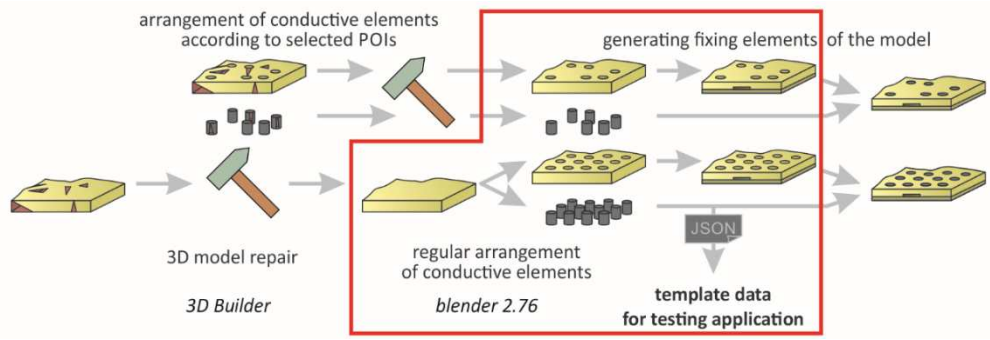


Figure 10. 3D modeling block scheme of the tactile map creation workflow.

Another open-source software, Blender [33], was used for the rest of the processing of the 3D models. This part consisted especially of generating primitive shapes (blocks, cylinders) at predefined locations according to the model size. These primitives were then either united or subtracted from the model. To automate the repetitive process, a Python script was developed to import both 3D models (interactive and noninteractive map parts), roughen the top surface of interactive map symbols, automatically place hooks on both sides of the maps in the suitable position according to the imported model size, and add the map symbol providing later basic information about the map and its content when touching it. The script also provided additional functionality to alternatively import one consistent model only, to generate interactive elements in a defined size and grid, and to export their position into a JSON file to be used in a mobile application (see the low branch

in Figure 10). This alternative functionality was not used in this case as it was implemented into the script for other types of 3D models. Final 3D models were exported by the script in a defined location in STL file format (both Binary and ASCII file may be used). Link to the Python script is available in the Supplementary Materials.

In the last part of the workflow (Figure 11), Slic3r [34] software was chosen to set printing parameters of both models to be printed using a Poseidon Duo 3D printer equipped with 0.4 mm nozzles. Precise calibration of the nozzles' height above the printing bed had to be done before launching the 3D printing process as it may influence the quality of the outcomes [16]. Otherwise, model parts printed by one nozzle could have been damaged by the second nozzle, and the adhesion of the model could be insufficient. Proto-pasta PLA filament was used for printing the conductive map elements, while blue non-conductive PLA was used for 3D printing of the non-interactive part of each tactile map. A layer height of 0.2 mm was used to reduce printing time because no continuous changes of the surface were present in case of the tactile maps. Using lower layer height would not, therefore, result in smoother surface. Infill of 60% was applied to keep especially the conductive parts durable enough. A temperature of 215 °C was set for both extruders and 50 °C for the printing bed. This, however, differs a lot according to the 3D printer and filament used. Therefore, no strict recommendations related to the printing temperature could be given. The printing time varied between two and three hours.

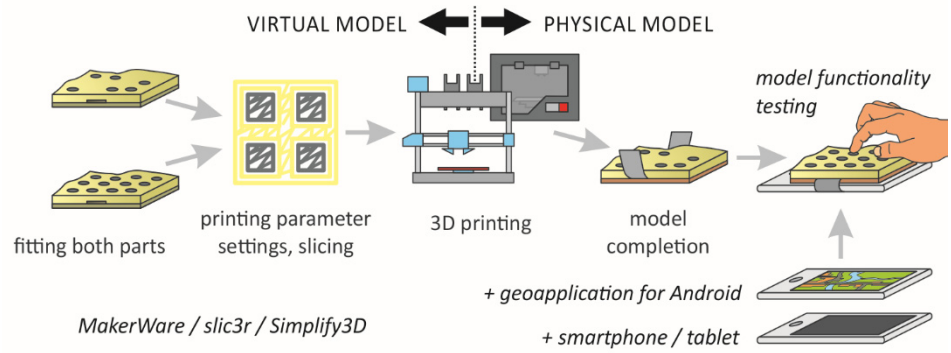


Figure 11. 3D printing block and map finalization scheme of the tactile map creation workflow.

Finally, button schemes containing text captions to be paraphrased by TTS were coded in the form of a JSON file importable into the TactileMapTalk [35] Android application developed especially for the TouchIt3D maps. It represents a simple application where software buttons are defined via a JSON file, and after touching these buttons, text of the caption associated with the button is read using the TTS function. This mobile application was used for testing in this case study. However, any other application or a simple website where software buttons can be defined may be used for TouchIt3D tactile maps. Proper functionality of each map (Figure 12) was tested to avoid some interactive map symbols not working due to incorrect button placement or 3D printing errors. The content of predefined texts and their adaptation by TTS was examined similarly. Reflecting the preliminary user survey, the mobile application was upgraded to launch the auditory description only when pressing an interactive map symbol for at least 1 s.

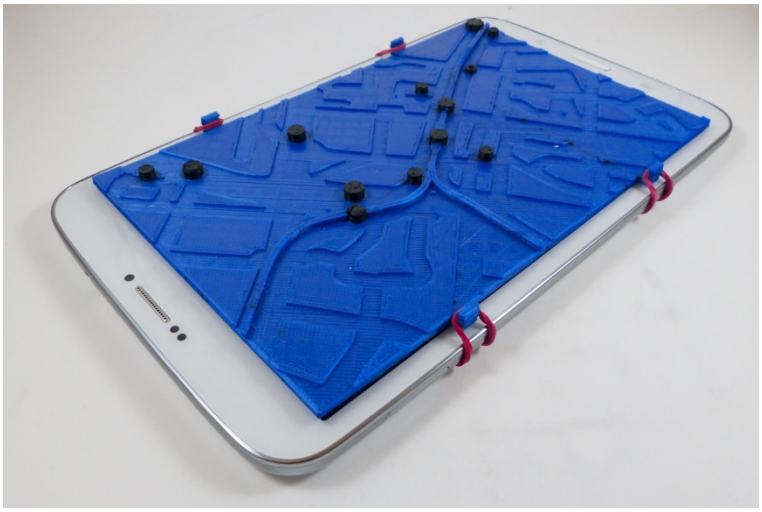


Figure 12. Final map of the Public Transport type capturing part of Ostrava's city center.

2.4. User Evaluation

User testing of final tactile maps was realized similarly to how the preliminary survey was done. This testing aimed to obtain feedback from people with visual impairment on the readability and usability of these interactive tactile maps made using semi-automated processes. Most respondents were the same participating in the preliminary survey, although some were new for the final testing and some respondents from the preliminary survey declined to join the final one. A total number of 10 respondents joined the evaluation, from which five identified themselves as female and the other five as male. All the respondents had used some kind of tactile maps before. The same sets of tasks were given to all respondents, while the interview part was kept unstructured and developed various topics varying between respondents. The results of the experiments were later confirmed on a larger user group in follow-up research testing a similar type of new-generation TouchIt3D tactile maps [36].

The meeting with each individual respondent was always introduced by presenting all three themes of the final tactile maps set in the uniform order from the simplest to the most complex one: Public Transport, Walking and Tourism maps. After explaining the content and functionality of each map, respondents were asked to finish a task related to that kind of map. In the case of the Public transport map, the given task (marked PT1) was to detect which tram line can be used to travel between two tram stops defined by their name and to which other means of transport they can transfer on one of these stops (PT2). For the Walking map, the tasks were to find the closest restaurant from a defined tram stop (W1) and to show the shortest path from the restaurant to a grocery shop (W2). In the Tourism map, respondents were asked to show and describe the path from a castle across the main town square to a specific hotel (T1). Additionally, they were asked to show where the areas covered by trees are situated on the map (T2).

Answers were marked as "correct" when respondents fully completed the task; as "partly correct" if they, for example, found a POI of the same type but not exactly the correct one, found the path but not the shortest one, and also if they showed forest but also showed another height layer in the task T2. Answers were deemed incorrect and marked "wrong" when the respondent indicated an incorrect map symbol or failed to finish the task at all. The final part of the testing utilized an interview format, in which respondents were asked to evaluate the distinctiveness of map symbols, the usability of presented maps and asked for suggestions they have for further development.

3. Results

The correctness of the answers from the user evaluation is captured in Table 2. Correct answers occurred almost in all cases for the simplest map of the Public Transport type.

With increasing map complexity, the success rate decreased. The majority of respondents answered the complex task T1 only partly correctly. It was expected that due to the presence of five different layers in the Tourism map type, there were also several mistakes in distinguishing the forested area in task T2.

Table 2. Evaluation of the tasks from user testing.

Resp.	Task PT1	Task PT2	Task W1	Task W2	Task T1	Task T2
1	correct	correct	correct	correct	partly correct	correct
2	correct	correct	correct	wrong	partly correct	wrong
3	correct	correct	partly correct	correct	partly correct	wrong
4	correct	correct	correct	correct	correct	correct
5	correct	correct	correct	correct	partly correct	correct
6	correct	wrong	correct	correct	correct	correct
7	correct	correct	correct	correct	correct	wrong
8	correct	correct	correct	wrong	partly correct	correct
9	correct	correct	partly correct	correct	wrong	correct
10	correct	correct	correct	partly correct	partly correct	partly correct

Similar to the preliminary survey, all respondents were very satisfied with the interactivity of the maps, which was the most distinguishing feature compared to other tactile maps they had worked with before. Half of the respondents stated the edges of map symbols were appropriately rough, while two said the edges were a bit sharp. The others did not mention this aspect. A few participants asked for an interactive symbol for muting and unmuting the auditory descriptions. This feature is currently being implemented in the new generation of TouchIt3D maps to avoid interruption during the introductory map exploration. Only one respondent suggested the auditory content be launched by double-click, whereas the rest described the current solution to be good or did not mention this being problematic. Abbreviated responses are shown in Table 3.

Additionally, the first respondent would appreciate having the map legend available separately. This participant experienced some problems with the unintentional launching of auditory descriptions. The second participant proposed having a more detailed scale for maps distinguishing individual buildings as he experienced difficulties touching the street surface when surrounded by buildings. In contrast, the fourth respondent joining the evaluation appreciated the large area covered by each map. She even stated that these maps were the most sophisticated tactile maps she had ever encountered (before, she experienced hand-made tactile maps, plastic foils, maps based on microcapsule paper, and few 3D printed tactile maps). The fourth and eighth respondents described themselves as "not map-based people" but were pleasantly surprised by the functionality and interactivity of the presented maps. While the sixth respondent suggested using these kinds of maps for orientating at exhibitions, concert halls, and railway stations, the seventh respondent, conversely, did not deem it useful to use these at train stations, which are generally equipped with navigation audio-beacons. Instead, she suggested that these maps could be very useful in hospitals. The last participant in the user testing suggested the idea of moving the interactive map symbols slightly so that they would be completely inside the buildings in order not to block a clear interpretation of street connectivity.

Table 3. Results of the final part (interview) of the user evaluation.

Resp.	Advantages	Disadvantages	Suggested Use
1	interactivity, rough edges, map readability	separate legend missing	walk planning, buildings
2	interactivity, map readability	larger scale preferred	inside and in front of offices
3	interactivity, map readability	"mute" missing	walk planning
4	interactivity, rough edges, small scale, functionality	–	independent movement practicing, education
5	interactivity, rough edges	–	when lost in a city
6	interactivity, rough edges, map readability	"mute" missing	exhibitions, concert halls, railway stations
7	interactivity, rough edges, map readability	–	Hospitals
8	interactivity, functionality	double-click better	walk planning, education
9	interactivity	sharp edges, "mute" missing	education, state offices
10	interactivity, symbol distinguishability	sharp edges, interactive symbols blocking streets	walk planning, education, busy places

Despite the lower initial costs, the maps were very positively evaluated by our respondent group of people with severe visual impairment. All participants of the map evaluation enjoyed the interactivity of the presented maps and achieved a geospatial awareness of the mapped areas. The tactile map of the Public Transport type with inaccessible areas merged into a single map layer was usually evaluated to be easily readable. Other map types, even when they suffered from occasional misreading, were appreciated for their detailed shapes. The scale of 1:4000 was suggested as optimal for this kind of plastic tactile maps due to its balance of both good readability and sufficient extent. Considering map symbology, four height layers appeared to be optimal for less-experienced readers, while for the more experienced users, five layers were comprehensible as well providing a more detailed image of the mapped area.

As a result of the final user verification, interactive TouchIt3D tactile maps linkable with a tablet were considered innovative and new for all respondents in the user evaluation. The people with visual impairment, joining the map presentation and testing, introduced many interesting ideas regarding how those maps could be used and upgraded. The ideas included using these maps for indoor navigation, for capturing hospitals, large railway stations, shopping malls, exhibition grounds, and similar spots. Some suggested using the TouchIt3D maps for independent movement education directly in the field, while others would prefer to use them prior to their movement in order to memorize the area. All the examples suggest the need for specific upgrades, and several will be examined in follow-up research.

4. Discussion

Although the proposed workflow has made the creation of multimedia tactile maps significantly more effective, it still involves a number of steps that must be performed manually. The reasons for this include the fact that some operations are necessary to be done manually considering the individual characteristics of tactile maps (e.g., appropriate descriptions for mapped objects). Difficulties in automation were also caused by poor interoperability between GIS and 3D modeling software. Additionally, the final phase of so-called slicing (converting a 3D model into simple instructions for a 3D printer) is highly dependent on the type of 3D printer used. It also cannot be automated while preserving the possibility to use different 3D printers. Therefore, it is assumed that a fully automated workflow would not be widely usable and with current specifics of 3D printers not even possible.

The developed workflow is also limited in the diversity of map symbols representing POIs. All the conversions of point data into polygons were made using the Buffer tool (a processing tool creating buffer polygons around input features to a specified distance). Therefore, all the symbols are round, varying only in diameter (public transport stops different than other POIs). However, which object is represented by each map symbol is clarified by the auditory description. Besides the other similar approaches, the presented workflow for TouchIt3D maps preserve the possibility to use both positive and negative 3D relief surface and advance the connection with a mobile device to provide additional information. At the same time, the map's simplicity is preserved.

Mostly, open-source software and open data like OSM were used in the workflow. Originally, open-source tools were intended to be also used for GIS geoprocessing analyses instead of commercial software. However, when the same operations were applied in the QGIS Graphic Modeler tool, the workflow consisting of multiple subsequent overlay analyses (Clip, Union, etc.) resulted in some invalid topology very often. Mostly, zero-width switchbacks/knots occurred along the boundaries of polygon layers. Unfortunately, these switchbacks/knots occurred even when implementing alternative open-source tools available in the QGIS list, and the result faulty layers were irreparable by common tools for repairing incorrect geometry. These errors either interrupted the automated workflow or would cause difficulties in the process of 3D modeling. Therefore, even though the workflow of subsequent operations in QGIS was correct and vocationally even resulted in usable output, the ArcGIS geoprocessing tools were used instead, providing correct results in all cases with clean topology without any switchbacks nor knots.

Even though it is difficult to calculate the final cost of each map, including the cartographer's time necessary for its preparation (which also differs worldwide), just a simple comparison of material costs shows the savings brought by the use of TouchIt3D technology in the financial aspects, while still keeping the map qualities.

While older-generation interactive maps [4,37] required costs reaching €350–400 (about €150–200 for the map and €200 for the electronics), one TouchIt3D map can be printed for €15; adding in a tablet costing €120 does not reach even half of this sum. Moreover, when using one tablet for ten tactile maps, the average price per map falls under €30. These savings were mostly achieved by: (1) using cheaper technology of 3D printing (low-cost 3D printers and cheaper filament instead of powder-based technologies), (2) using a tablet for multiple maps instead of mounting electronics into every single map, (3) using open-source data and sources. The costs of commercial software were not counted in costs before nor after the optimization as a university license was used in both cases. More savings could also be expected to be achieved due to a less time-consuming design process, but the impact of this aspect cannot be fully calculated due to diversity in labor costs.

Production of TouchIt3D interactive maps remains, of course, more expensive compared to simple non-interactive 3D tactile maps [19,20,27]. Furthermore, it involves a multi-extruder 3D printer that is not necessary for maps made of one material or maps with colors variable only in the height direction. However, the interactivity of tactile maps was found to be very important for people with severe visual impairment when exploring the exterior in this study, similarly to the importance when orienting indoors [17]. Among older studies [17,18], our approach presents interactive maps which are easily portable and usable both in the interior (for studying the landscape in advance) and in the exterior (e.g., when moving in a city). Henceforward, automatic generalization of input data (e.g., simplifying shape of polygon features), delineated by some studies [28], has remained an unresolved issue and has been implemented neither in our study. Yet, some basic cartographic generalization was secured by overlay analyses in the process of data processing.

5. Conclusions

The study introduced interactive TouchIt3D tactile maps designed using a semi-automated workflow. The principle based on linking a plastic tactile map with a tablet

brought significant time and financial savings valuable in the field of tactile cartography. A workflow automating some parts of the map design process reaching from data collection through the preparation of a mobile application template up to the 3D printing enabled the creation of an interactive tactile map in less than one day. This workflow is several times faster than previous multimedia tactile maps.

Many new suggestions and a large amount of feedback were noted during both user experiments. There was no consensus between respondents on some issues, illustrating the diversity of people with visual impairment and their aims. However, several clear messages indicated the direction for further development and use of the TouchIt3D technology. The responses from the final user evaluation were implemented in the new generation of the TouchIt3D tactile maps in the follow-up studies. Ongoing research has focused on the use of interactive tactile maps for independent movement education and the perception of geospatial features via interactive 3D models.

Supplementary Materials: The three ArcGIS Model Builder models used for processing the GIS data are available online at www.radiat.cz/research/TactileMap.tbx and the Blender extension for finalizing the model is available in the form of Python script online at www.radiat.cz/research/blenderScript.py.

Author Contributions: Conceptualization, Radek Barvir, Jan Brus and Alena Vondrakova; methodology, Radek Barvir; software, Radek Barvir; validation, Radek Barvir, Jan Brus and Alena Vondrakova; formal analysis, Jan Brus; investigation, Radek Barvir; resources, Alena Vondrakova; writing—original draft preparation, Radek Barvir; writing—review and editing, Alena Vondrakova; visualization, Radek Barvir; supervision, Jan Brus; project administration, Alena Vondrakova. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data used in the research presented in this article will be made available by the authors upon request, without undue reservation.

Conflicts of Interest: The authors declare no conflict of interest.

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APPENDIX 11

Creating a Haptic 3D Model of Wenceslas Hill in Olomouc

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Article

Creating a Haptic 3D Model of Wenceslas Hill in Olomouc

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Abstract: Interactivity in today's society finds its way into many facets of life and can be used in various ways, including 3D printing. For example, various 3D models can be incorporated into museum exhibitions and serve as interactive media for visitors, deepening their experience. One of the advantages of haptic 3D models is the immediate haptic feedback. Such models can have various uses, from being a part of an interactive exhibition to providing assistance to people with visual impairment. This article describes the process of creating a haptic 3D model depicting Wenceslas Hill in Olomouc in the eighteenth century. The model has several surface elements printed from conductive material that react to touch. The interactive model itself is unchanged from its original modelled 3D version, meaning the shape of the object stays the exact same throughout modifications. The resulting model conveys additional information about the object or its parts by means of a web interface via a connected tablet device. To implement the desired functionality, TouchIt3D technology was used. This technology uses a combination of conductive and non-conductive materials for 3D printing. The conductive material serves to propagate an electrical signal caused by touching a chosen part of the model. A 3D printer with two extruders was used for printing the model, allowing simultaneous printing of two different materials. The model's scalability is advantageous for potential use by people with visual impairment. The model shall serve as a tool for enriching historical knowledge about the object by using interactivity.

Keywords: interactivity; TouchIt3D; 3D model; 3D printing

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1. Introduction

Interactivity can be perceived as a process of executing an action based on a previous action. In today's world, it is used in many ways as people expect a specific form of interactivity in everyday life. However, physical interaction with displayed historical objects is forbidden in most conventional museums. This restriction is imposed because various objects of natural or cultural character have to be preserved for future generations [1].

There are many approaches to presenting models in museums, especially in the context of education. One approach is tailoring the visitor's experience to provide choice. Each visitor should be free to choose which objects they want to interact with. This choice can then support their curiosity [2], and most modern science museums that present natural phenomena try to present them in an interactive way. This approach encourages the visitor to explore and experiment [3]. Interactivity can be achieved by 3D printing to create an interactive 3D model. By using 3D printing, users can use haptic feedback to interact with objects. The physical objects can be recreated in a 3D environment and manufactured using 3D printing. Various items in cultural heritage are 3D printed to make fairly precise replicas of existing originals [4]. Physical interaction with the objects is then possible. Combining interactivity and 3D printing is one of the ways of creating a historical object containing parts that react to a user's touch and presenting additional data about the object or its parts, bringing forward information that is not usually obtained in museum exhibitions.

Another way to convey information interactively is by using an application with 3D touch controls implemented via a multi-touch table while focusing on UX (user experience) aspects

and guided inquiry [5]. Nakamura and Yamamoto [6] have also researched haptic feedback implemented via a multi-touch display. Additional related studies were presented by Ciolfi and Bannon [7], Gammon [8] and Csikszentmihalyi and Hermanson [9]. 3D printing can be used in various subject areas, with one of the more prominent being cultural heritage (CH). In recent years, the accuracy of 3D printing has increased considerably so it is feasible to present more visually pleasing and accurate results in the field of CH [10]. There are many ways of preserving historical artefacts for future generations, with 3D printing being one of them, and especially significant for creating tangible models [11]. Digitalisation and subsequent 3D printing of objects can be used to reconstruct and preserve objects of historical importance throughout various disciplines. Further studies on this topic include Laycock et al. [12], Balletti and Ballarin [13], and Al-Baghdadi [14]. Virtual Reality (VR) technology is also a significant contributor to CH, as it can enhance interactivity with printed 3D models [15] or provide 3D visualisation of objects generated via photogrammetry [16].

A multitude of ways to provide interactivity using 3D printing have been employed. For example, a 3D model can be combined with electronic parts such as a position sensor and computer for visualisation [17]. Sarik et al. [18] have also studied a similar topic. Another solution for providing interactivity is subtracting material from 3D models so that they can, thereafter, be filled with pipes distributing various substances. Depending on the substance used, there are different interactive effects, such as reacting to proximity or touch [19]. It is also possible to use 3D printing from conductive materials to create tangible models for information sharing and information selection using, respectively, BYOI (Bring Your Own Information) and BYOT (Bring Your Own Tool) principles [20]. Notably, 3D printing can also serve to transfer user input from a model to a touch device, using conductive PLA [21]. Other interactive 3D methods include using a web-based environment making use of 3D scanning data [22] or virtual reality using CAD (computer aided design) data [23]. Other ways of combining interactivity and 3D models have been researched by Willis et al. [24], Li et al. [25] and Liu et al. [26].

3D printing can also be used to assist people with visual impairment. Examples include using 3D tangible maps made from conductive material, connected to a mobile device to help with route planning when going shopping etc. [27]. The use of conductive material became a topic of interest for other researchers, such as Taylor et al. [28], Schmitz et al. [29] and Götzelmann [30]. Götzelmann and Althaus [31] provide an approach for enabling touch sensitive surfaces on existing 3D objects using a set of conductive parts. Three-dimensional models can also be used to help with education of the visually impaired, allowing the relay of information about abstract concepts, which are otherwise not easily conveyable [32]. Additional studies on the subject include Thevin and Brock [33] or Shi et al. [34]. Another interesting approach to creating interactive 3D models for people with visual impairment is to use a 2.5D display capable of adjusting a 3D model in real time via programmable scripts, and thus providing instant haptic feedback [35]. Similar programmable 3D models have also been a research interest for Leo et al. [36]. Other notable examples of providing haptic feedback include a so-called haptic edge display that provides tactile interactions for mobile devices by the use of tactile pixels, which are implemented using piezoelectric actuators [37].

The 3D model presented in this paper provides audio-visual feedback based on haptic interaction. It is also capable of providing information about the historical state of the object of interest by means of observation, as it captures the area of Wenceslas Hill in the eighteenth century. Combining this with the aforementioned haptic feedback can point out the differences between seeing and touching an object. The model is easily replicable by any printer with multi-material capabilities or dual extrusion, as it does not rely on any additional electronics, except for the tablet computer. When factoring in filament pricing and the amount of filament spent, printing out the model costs around 30 USD. The shape of the model does not deviate from the original and, as such, is a representation of the historical object, which is valuable for cultural heritage and object preservation. The model and its functionality show the possibilities of TouchIt3D technology and could serve as a template for similar solutions, as it is a unique approach to creating haptic 3D models.

This paper is structured as follows: Section 2 presents the methods used to create the haptic 3D model, including the TouchIt3D technology, workflow to implement the technology, designs for connecting multi-part 3D models and web interface design. Section 3 describes the achieved results, notably the haptic 3D model of Wenceslas Hill and the web interface that serves to present additional information. Section 4 describes various issues of the resulting 3D model and compares it and its functionality to similar studies. Section 5 then concludes the paper.

2. Materials and Methods

This article aims to describe the process of creating an interactive haptic 3D model of Wenceslas Hill in Olomouc, which depicts its historical state and is accompanied by a tablet computer that serves to present additional information. To fulfil the said goal, TouchIt3D technology was used [38]. The 3D model contains several surfaces that react to touch, providing interactivity. For a user-friendly way of displaying desired information about the object or its parts, the tablet computer serves as a part of the resulting model. In addition, several solutions for conducting an electrical signal in the case of the models, which are composed of multiple parts, were designed. The created haptic 3D model holds an ambition to serve as a tool for enriching knowledge about the given area.

Wenceslas Hill is located in the city of Olomouc, Czech Republic. On the top of Wenceslas Hill, Olomouc Castle is situated. There are many significant places of interest in the area of the castle, with the most distinctive one being Saint Wenceslas Cathedral [39]. Other places of interest include a partly preserved Romanesque palace, and the Chapel of St. Anne and Chapel of St. Barbara. The area has seen a multitude of architectural makeovers throughout history, especially the cathedral. The model described in this article depicts the area of Wenceslas Hill in the eighteenth century. The current appearance of some of the buildings in the area is shown in Figure 1.



(**a**) (**b**)

Figure 1. The current appearance (as of the year 2022) of Saint Wenceslas Cathedral (**a**) and Chapel of St. Anne (**b**) (source: authors).

The basis for creating the printed interactive model was a 3D model of Wenceslas Hill in Olomouc, depicting the area in the eighteenth century. The model was originally designed as part of a time series of 3D models presenting Wenceslas Hill in several historical periods. For the process of 3D modelling, SketchUp (sketchup.com) ver. 18 from Trimble was used. The model contains 180,108 polygons. Most of the polygons (121,078) form a generated digital terrain model (DTM), which serves as the model base. Without the DTM, the rest of the model has 59,102 polygons. The model was modelled in LOD 3 [40]. It was created by referencing available historical material from the target time period (e.g., sketches, historical drawings) for the Olomouc Museum of Arts. The eighteenth century model was chosen mainly due to a suitable level of detail for modifying and subsequently printing the model.

TouchIt3D technology served to design the conductive parts of the model and create designs for conducting electrical signals for 3D models composed of multiple parts. The idea behind TouchIt3D is to provide interactivity by combining a device with a touchscreen with a model printed on a 3D printer. The technology uses a combination of conductive and non-conductive materials for 3D printing. The material used for printing was polylactic acid (PLA), both for the conductive and non-conductive parts. The basic principle of TouchIt3D technology is the use of any 3D model with parts modelled for the purpose of being printed using conductive material. The conductive part, containing carbon, reacts to touch and can then conduct an electrical signal. To provide interactivity, the technology is accompanied by a touchscreen device with interactive virtual buttons. Upon touching a chosen conductive part, additional information about the conductive part is shown on the display of the device. The technology was implemented using the process of 3D modelling that served to design and place parts of the model, which are to be conductive in the resulting printed model. Figure 2 shows the steps needed to implement the TouchIt3D technology. When implementing the technology, a workflow was followed to ensure proper functionality. The workflow is presented in detail in Section 2.3. The model was printed on Craftbot FLOW IDEX XL. This 3D printer has two extruders and, therefore, provides an option of simultaneously printing two materials (conductive and non-conductive filament). Proto-pasta PLA was chosen for the conductive parts and Polymaker PolyMax PLA for the non-conductive parts.

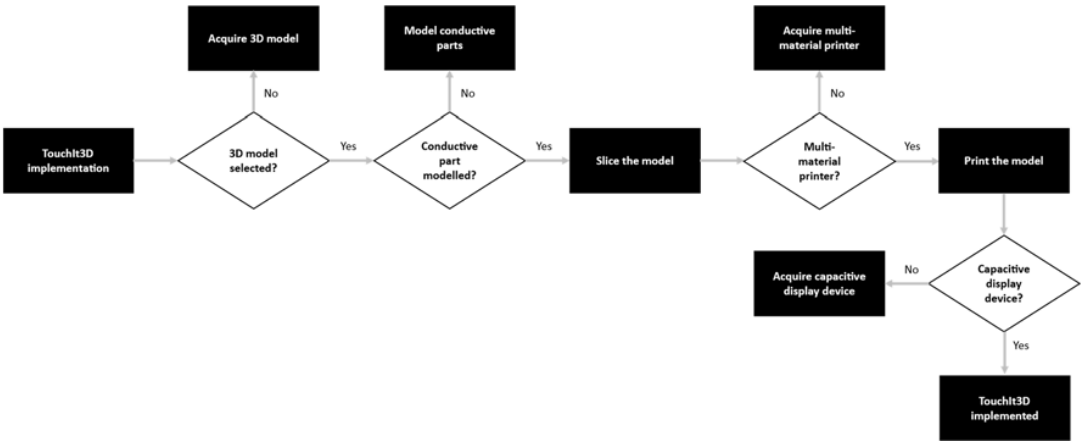


Figure 2. TouchIt3D implementation steps. Notably, a 3D printer with multi-material capabilities or dual extrusion is needed to implement the technology, as well as a device with a capacitive display.

SketchUp was used for creating the conductive parts of the model and modifying the base part of the model, enabling accommodation of the tablet computer. It was also used for minor modifications of both the conductive and non-conductive parts, and modelling the designs for conducting electrical signals in multi-part 3D models. Each presented design consists of two standalone cubes of fixed dimensions. One of the cubes contains a conductive surface and a tube, also conductive, which serves to connect the parts. The second cube contains the rest of the conductive tube and an extended surface designed to be in direct contact with a touchscreen display. The designs aimed to find a suitable way of connecting two standalone parts that would allow for an electrical signal to be conducted. Another important part of creating the haptic model was subtracting the conductive and non-conductive parts. For this purpose, Netfabb Premium ver. 2021.1 was used. The aforementioned software was utilised to execute Boolean subtraction of the model parts. Netfabb was also used to repair the 3D models' geometry errors, making them manifold and correcting inverted or intersecting faces, using mainly automatic repairs. Some repairs, however, needed to be done manually, which was achieved in SketchUp.

CMS (content management system) WordPress was used for creating a web interface that would display additional information. The interface needed to be very specific.

Therefore, a custom WordPress theme was created using the PHP programming language, HTML5 markup language and CSS3. Before printing the model, a so-called G-code containing a series of instructions for the 3D printer had to be generated from the 3D model. For this purpose, Ultimaker Cura ver. 4.8.0 was used. Before generating the G-code, layer height and infill density settings were adjusted. Layer height was set to 0.1 mm and infill density to 15% for both extruders. Afterwards, the model was sliced, generating the G-code.

The functionality of the 3D model and web interface has been tested and validated by the authors. The principles, functionality and detailed setup of the TouchIt3D technology have been tested in various application scenarios as the technology plays a significant role in past and currently ongoing projects at Palacký University Olomouc, mostly focused on working with people with visual impairment and partially sighted people [41].

2.1. Conducting Electrical Signal for Multi-Part 3D Models

In the process of creating the haptic 3D model, several designs for conducting electrical signal connections in the case of multi-part 3D models were made. Five designs were created in total, each composed of conductive and non-conductive parts, created using Boolean subtraction. Each design was modelled, printed and tested. The testing showed that only two out of five designs provided the expected functionality. One of the models was printed out in a non-intended way, effectively making it functional despite the imprecise printing process. The mentioned model was originally designed to contain an element of cylindrical shape that would serve to connect two standalone cubes. However, in the final print, the cylindrical element was entirely absent. The model, therefore, only contained two flat conductive surfaces that were in contact with each other, providing the desired effect. The only other valid design was one with a convex and a concave side that precisely joined to each other to conduct an electrical signal. The other designs failed in the ability to conduct an electrical signal, which was mainly caused by imprecisions in the 3D printing process. The resulting designs are shown in Figure 3.

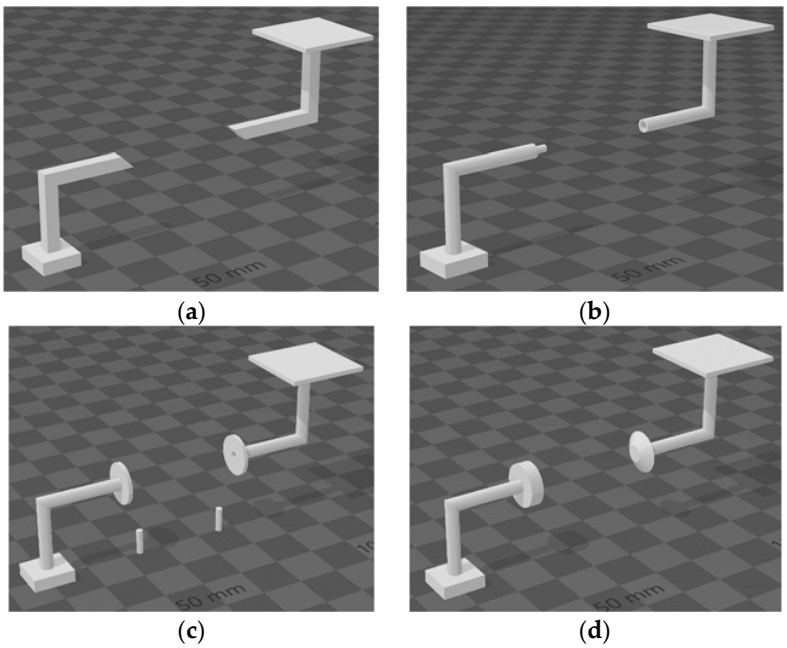


Figure 3. Modelled designs for conducting an electrical signal between distinctive parts of a 3D model. (**a**) Sloped surfaces proved to be an invalid solution. (**b**) Another non-functional solution, given by the imprecisions of 3D printing. (**c**) A valid solution, but also influenced by imprecisions and absent model parts, as described in the text above. (**d**) A valid solution; the shape of either side is not prone to imprecisions that stem from 3D printing.

2.2. Designing the Web Interface

The web interface, extending the model functionality by displaying additional information, was designed in such a way that it could be used and modified even by people without any knowledge of either HTML or CSS. To achieve this, CMS WordPress was used, as it allows for modifying the content, from rewriting text to adding an image or a video, all without the need to edit the code itself, making it an effective tool for content management. Since the web interface needed to be very specific, it was decided to create a custom WordPress theme. The interface consists of an intro page with a list of the selectable conductive parts and quick guide on interacting with the model. Since the model has eight conductive elements in total, the interface navigation menu has eight links, each providing additional information about the chosen part of the model in the form of written text and images. It is possible to modify the content shown based on preferences or feedback from users.

2.3. Workflow for Creating a Haptic 3D Model

The presented workflow could, with minor modifications, be used for essentially any 3D model. The workflow results in a 3D model containing surfaces printed from conductive material. Such a model can be combined with a device equipped with a capacitive display, and therefore react to electrical impulses caused by touch. The key step of the workflow is designing and modelling parts that are conductive while following several requirements for the final product to function properly. In particular, it is crucial for the surfaces in contact with a display to have a large enough size. If the size is too small, the propagation of the electrical signal is not sufficient and functionality is limited. Another requirement is sufficient distance between conductive elements, assuring they do not cross each other inside the model. The next step of the workflow is doing Boolean subtraction of conductive and non-conductive parts. The subtraction takes two 3D models as input—the original model and the separate conductive part, which was previously designed and modelled. After executing the subtraction, a model with gaps representing the non-conductive part is created. Before executing the subtraction, it may optionally be necessary to repair small geometry errors of the 3D models. The amount of errors depends on the quality of the original 3D models. If the repairs are not made, it could result in the subtraction not executing properly. This operation can be performed either manually or by using automatic repair tools, e.g., those implemented in Netfabb and 3D Builder software. When having two standalone models for the conductive and non-conductive parts, different printing parameters can be set for each part, using a so-called slicer (e.g., Ultimaker Cura, PrusaSlicer). In the slicer, a preferred printing material can be set for each part, after which the parts should be joined together again, forming one object. The next step is the 3D printing itself. Before proceeding with the printing process, it is possible to set various properties of the printing process, such as layer height, or enabling the so-called Wipe Tower, which is used when printing from two different filaments. The tower serves to clean the nozzles of the extruders when changing filament. Even if a 3D printer capable of dual extrusion is used, it is still recommended to use the Wipe Tower to prevent the materials from blending. After preferred printing properties have been set, the model can be sliced, generating G-code, and finally printed (Figure 4).

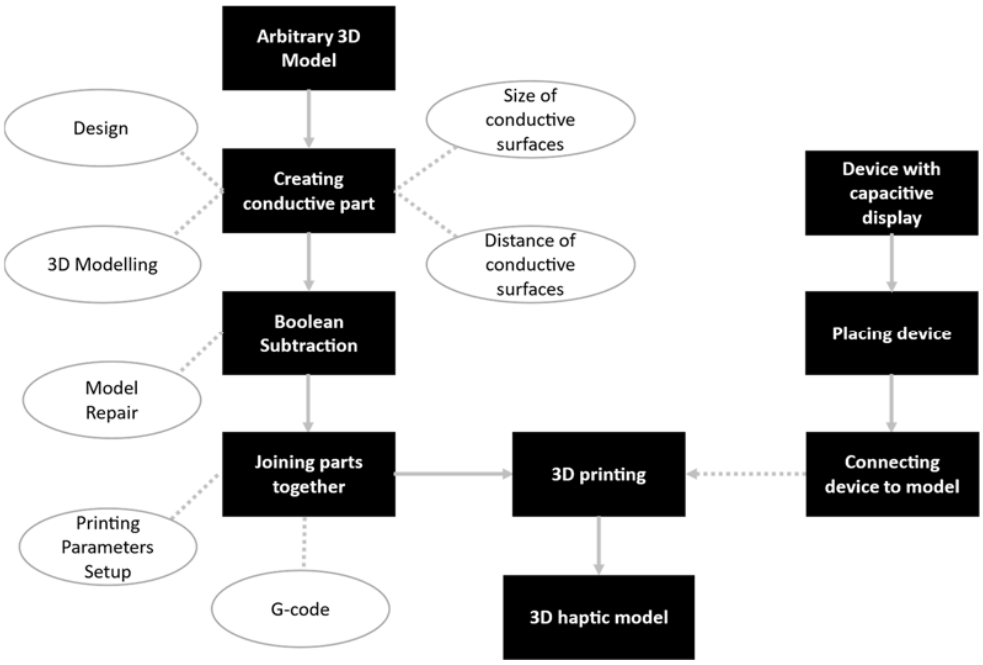


Figure 4. Workflow for creating a haptic 3D model. Any 3D model can be processed with the presented steps, implementing the TouchIt3D technology.

3. Results

3.1. Haptic 3D Model of Wenceslas Hill

The resulting haptic 3D model of Wenceslas Hill is based on a 3D model capturing the state of the object in the eighteenth century (Figure 5). The haptic model is composed of three parts: a conductive part, non-conductive part and model base. The conductive part contains eight conductive elements in total, printed using conductive PLA Proto-pasta filament to provide interactivity. Each conductive element consists of one or more conductive surfaces, a 3 mm diameter conductive tube and a block with a rectangular surface that is designed to be in contact with a touchscreen device (Figure 6). The conductive elements are designed not to cross each other and also to allow sufficient distance for the electrical signal to be insulated.

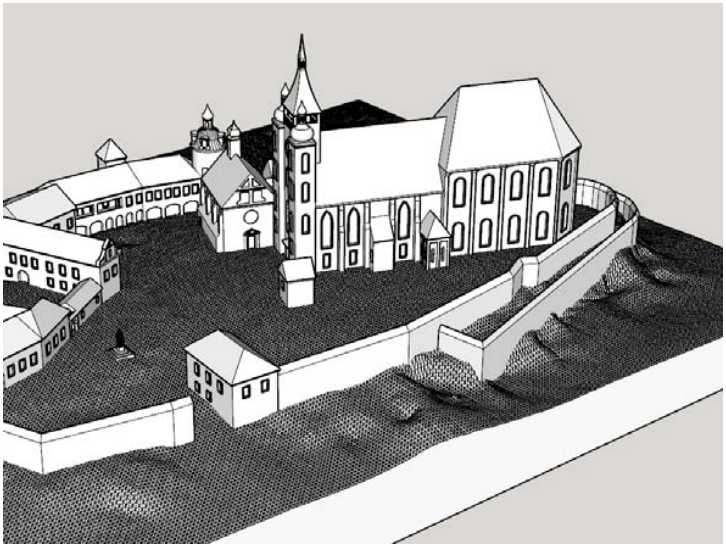


Figure 5. The original state of the 3D model before any modifications (e.g., adding the conductive part) were made.

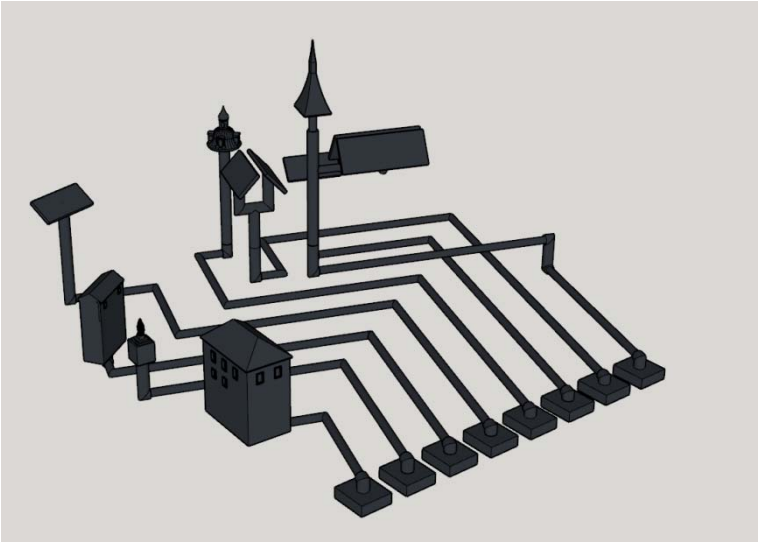


Figure 6. The conductive part of the haptic model. There are 8 parts in total, each one composed of either one or more conductive surfaces.

The non-conductive part was obtained as a result of Boolean subtraction between the original 3D model and created conductive part. The subtraction resulted in a model with gaps located in areas where the original model and conductive part would intersect. In other words, after putting the conductive and non-conductive parts together, the missing material is filled out with conductive material. After combining the two parts and finally printing them, the main segment of the model was established, as shown in Figure 7.



Figure 7. The main segment of the resulting 3D model, composed of conductive and non-conductive parts. The conductive parts react to touch.

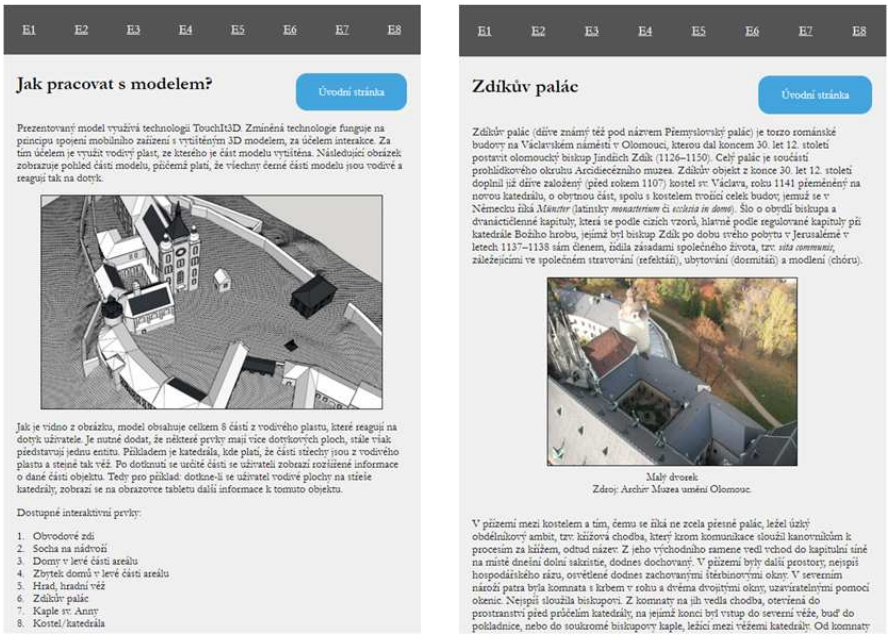
Furthermore, the model base was designed to create enough room for the computer tablet to fit in and prevent any sort of manipulation with the device, which could result in the model not functioning properly. When printing the model, the main segment was printed first, followed by the base part. Neodymium magnets, one in each corner of the model base, were used to join the whole setup together (Figure 8), enabling the desired functionality.



Figure 8. Haptic 3D model of Wenceslas Hill. It is composed of the main segment and modified model base. The tablet device for displaying the content is also shown.

3.2. Web Interface

The implemented web interface serves to display additional information about the model. It contains eight virtual buttons in the website header, each one linked to one or more conductive surfaces. Touching a conductive surface provides the same functionality as interacting with a touchscreen. Upon touching a conductive surface, an electrical signal is sent and the corresponding link is pressed. The web is then redirected to a page containing additional details about the chosen part. In addition, the interface contains a main page with basic information as well as a page describing how to interact with the models and also listing the available interactive parts of the model. The instructions are available from the main page via a separate virtual button available on the upper right of the web. Users can also return to the main page at any time via the same button (when not already on the main page). Figure 9 shows the web interface without the tablet attached, so the virtual buttons in the header can be seen. As the web is made in WordPress, the content can be easily extended and customised.



(**a**) (**b**)

Figure 9. The web interface shows additional information about parts of the model. Since the model was originally made for the Olomouc Museum of Art in Czechia, the content is in Czech due to the majority of Czech visitors in the museum. (**a**) The page containing instructions on interacting with the model. (**b**) One of the pages with additional information about a chosen part.

4. Discussion

The resulting 3D haptic model was created in the scale of 1:1000, which was influenced by several factors. The dimensions of the print bed of the Craftbot FLOW IDEX XL are 425 × 250 × 500 mm, which resulted in the need to limit the size of the printed model so it would fit on the bed. It would potentially be possible to print a larger model composed of multiple parts which could then be joined together. However, this would lead to an increase of total print time. Even in the scale of 1:1000, the total print time was roughly four days. If the model were enlarged by a mere 10%, the time would significantly increase. The dimensions of the model were also influenced by the number of interactive elements. Theoretically speaking, the model could contain more than eight elements, but to provide enough insulation distance between each element, their number was limited. The size of the tablet computer was also taken into account when deciding the scale of the final model.

The resulting haptic 3D model has several issues, unfortunately. The conductive Protopasta PLA, used to print the conductive part, suffered from an unwanted trait of leaving marks on the non-conductive white part. Since black and white are contrast colours, the mixing of the materials was visually obvious, fortunately without any functionality limitations. If the non-conductive part were printed using a different colour filament, these visual issues could have been alleviated. Another issue of the model is its technical shortcomings. The tablet computer needs to be placed in a very specific way without being manipulated later. The conductive elements also have to be in direct contact with the display of the tablet. If the model is then moved in any way, the intended functionality could be prevented. These shortcomings can be solved by a more precise modelling process and by pressure using foam material.

On the other hand, the presented solution has several advantages when compared with similar products, such as the model of Kroměříž Castle, created at the Department of Geoinformatics, Palacký University several years ago [42] (p. 110). The model also uses a tablet computer to present additional information upon touching a conductive part. However, about half of the display was covered by the model limiting the display potential, which is not the case for the haptic model of Wenceslas Hill. Here, only a small part of the display is covered by the model, providing more space for text, images and other forms of media. If some modifications were made, e.g., making the model larger or providing a different solution for connecting the tablet to the model, it would be possible to use a larger device to display the information. Similar to [20], the contents of the web could even be transferred to a much larger screen (e.g., monitor, TV) to display more information. Currently, the web is set specifically for the resolution of the device used. However, as the web uses CSS, multiple breakpoints could be set to control the layout of the content on larger displays. The styling and overall presentation of the web could be improved as well.

Contrary to the solutions presented in [17,31,37], the haptic 3D model of Wenceslas Hill does not rely on internal electronic components for its functionality and as such is easier to produce. In other words, no additional parts are needed for the intended functionality, as an electrical signal transfers through the conductive filament without any additional components. However, a device is then needed to interpret the signal, thus the presence of the tablet computer, which is in direct contact with the conductive parts. The need for a 3D printer with multi-material capabilities or dual extrusion could be seen as a drawback. On the other hand, the model is otherwise relatively cheap to produce. As the model itself does not rely on any additional components, it is easily replicable and its principles applicable to any other 3D model.

While the use of conductive filament lends itself quite well to the purposes of making 3D models for people with visual impairment, as seen in [27,28,30], the model presented in this paper serves primarily for sighted people and as such, it focuses on providing information via the web interface. However, it is scalable, so when modified, it could be suitable for people with visual impairment. The model even incorporates choice and experimentation as described in [2,3], as users are free to choose the part of the model they want to interact with and, in turn, which content they want to display. The content of

the web can be changed if the need to present different information arises. However, the number of conductive surfaces and, therefore, the number of interactive links in the header of the web stays the same.

5. Conclusions

The result of the presented article is the haptic model of Wenceslas Hill in Olomouc, capturing the object's appearance in the eighteenth century. Using TouchIt3D technology, the model was made interactive, providing additional information to users. Each interactive element was represented by a corresponding feature in the developed web interface. The information is presented upon touching a chosen conductive surface. The content of the web interface changes according to the surface selected by a user, making it possible for the user to choose only the desired parts, obtaining only the desired information. The additional information is shown on the majority of the display surface.

It is also possible to perceive the historical look of the object from just looking at the 3D model itself. However, the experience is enhanced by conveying additional information that can be tailored to provide relevant historical facts or historical context. It is not difficult to imagine there could be multiple models, each showing the object in a different time, together serving as a showcase of the historical development of a building or any other historical site. The usage of 3D printing provides multiple advantages, mainly the ability to touch objects without the fear of damaging them. 3D printing is also a cheap solution for small-series production. Therefore, in the case of a model being damaged, a spare one can easily be printed, making it much less expensive than using castings or other fabrication methods. Conversely, the disadvantage of 3D printing is the time necessary to print out the final product. Various 3D models, like the one presented, can be used in museum exhibitions, not limited to showing a historical state of an object. Similar principles can be applied for a wide range of geovisualisations, even ones of a technical nature, explaining their functionality and other aspects.

The haptic model can also be used to provide people with visual impairment with valuable information, lowering their information deficit. For this purpose, the model would have to be modified to suit the needs of this target user group, which could, for example, be achieved by adding the text-to-speech function. The basic functionality would be preserved though.

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