

This is an electronic reprint of the original article.

This reprint *may differ* from the original in pagination and typographic detail.

Author(s): Mihaela C. Ion, Caitlin C. Bloomer, Tudor I. Băräscu, Francisco J. Oficialdegui, Nathaniel F. Shoobs, Bronwyn W. Williams, Kevin Scheers, Miguel Clavero, Frédéric Grandjean, Marc Collas, Thomas Baudry, Zachary Loughman, Jeremy J. Wright, Timo J. Ruokonen, Christoph Chucholl, Simone Guareschi, Bram Koese, Zsombor M. Banyai, James Hodson, Margo Hurt, et al.

Title: World of Crayfish™: a web platform towards real-time global mapping of freshwater crayfish and their pathogens

Year: 2024

Version: Published version

Copyright: The Author(s) 2024

Rights: CC BY 4.0

Rights url: <https://creativecommons.org/licenses/by/4.0/>

Please cite the original version:

Ion, M. C., Bloomer, C. C., Băräscu, T. I., et al. (2024). World of Crayfish™: a web platform towards real-time global mapping of freshwater crayfish and their pathogens. PeerJ, 12 : e18229.

<https://doi.org/10.7717/peerj.18229>

All material supplied via *Jukuri* is protected by copyright and other intellectual property rights. Duplication or sale, in electronic or print form, of any part of the repository collections is prohibited. Making electronic or print copies of the material is permitted only for your own personal use or for educational purposes. For other purposes, this article may be used in accordance with the publisher's terms. There may be differences between this version and the publisher's version. You are advised to cite the publisher's version.



World of Crayfish™: a web platform towards real-time global mapping of freshwater crayfish and their pathogens

Mihaela C. Ion^{1,*}, Caitlin C. Bloomer^{2,*}, Tudor I. Bărăscu³, Francisco J. Oficialdegui⁴, Nathaniel F. Shoobs⁵, Bronwyn W. Williams⁶, Kevin Scheers⁷, Miguel Clavero⁸, Frédéric Grandjean⁹, Marc Collas¹⁰, Thomas Baudry⁹, Zachary Loughman¹¹, Jeremy J. Wright¹², Timo J. Ruokonen¹³, Christoph Chucholl¹⁴, Simone Guareschi¹⁵, Bram Koese¹⁶, Zsombor M. Banyai^{17,18}, James Hodson¹⁹, Margo Hurt²⁰, Katrin Kaldre²⁰, Boris Lipták^{4,21}, James W. Fetzner²², Tommaso Cancellario²³, Andrés Weiperth²⁴, Janis Birzaks²⁵, Teodora Trichkova²⁶, Milcho Todorov²⁶, Maksims Balalaikins²⁵, Bogna Griffin²⁷, Olga N. Petko²⁸, Ada Acevedo-Alonso²⁹, Guillermo D'Elía³⁰, Karolina Śliwińska³¹, Anatoly Alekhovich³¹, Henry Choong³², Josie South^{33,34}, Nick Whiterod^{35,36}, Katarina Zoric³⁷, Peter Haase^{38,39}, Ismael Soto⁴, Daniel J. Brady⁴⁰, Phillip J. Haubrock^{4,39,41}, Pedro J. Torres⁴², Denis Şadrin²⁸, Pavel Vlach⁴³, Cüneyt Kaya⁴⁴, Sang Woo Jung⁴⁵, Jin-Young Kim⁴⁶, Xavier H.C. Vermeersch⁴⁷, Maciej Bonk⁴⁸, Radu Guiuşu⁴⁹, Muzaffer M. Harlioğlu⁵⁰, Jane Devlin⁵¹, Irmak Kurtul^{52,53}, Dagmara Błońska⁵⁴, Pieter Boets⁵⁵, Hossein Masigol²⁸, Paul R. Cabe⁵⁶, Japo Jussila⁵⁷, Trude Vrålstad⁵⁸, David V. Beresford⁵⁹, Scott M. Reid⁵¹, Jiří Patoka⁶⁰, David A. Strand⁵⁸, Ali S. Tarkan^{54,61}, Frédérique Steen⁷, Thomas Abeel⁶², Matthew Harwood³⁴, Samuel Auer⁶³, Sandor Kelly⁶⁴, Ioannis A. Giantsis^{65,66}, Rafał Maciaszek⁶⁷, Maria V. Alvanou⁶⁵, Önder Aksu⁶⁸, David M. Hayes⁶⁹, Tadashi Kawai⁷⁰, Elena Tricarico⁷¹, Adroit Chakandinakira⁷², Zanethia C. Barnett⁷³, Ştefan G. Kudor⁷⁴, Andreea E. Beda⁷⁵, Lucian Vilcea⁷⁶, Alexandru E. Mizeranschi^{28,77}, Marian Neagul²⁸, Anton Licz⁷⁸, Andra D. Cotoarba⁷⁹, Adam Petrussek⁸⁰, Antonín Kouba⁴, Christopher A. Taylor² and Lucian Pârvulescu^{28,79}

Submitted 1 May 2024
Accepted 13 September 2024
Published 14 October 2024

Corresponding author
Lucian Pârvulescu,
lucian.pârvulescu@e-uvt.ro

Academic editor
Praveen Korla

Additional Information and
Declarations can be found on
page 17

DOI 10.7717/peerj.18229

© Copyright
2024 Ion et al.

Distributed under
Creative Commons CC-BY 4.0

OPEN ACCESS

¹ Institute of Biology Bucharest, Romanian Academy, Bucharest, Romania

² Illinois Natural History Survey, Prairie Research Institute, Champaign, IL, United States of America

³ Qtibia Engineering, Râmnicu-Vâlcea, Romania

⁴ Faculty of Fisheries and Protection of Waters, South Bohemian Research Centre of Aquaculture and Biodiversity of Hydrocenoses, University of South Bohemia in České Budějovice, Vodňany, Czech Republic

⁵ Museum of Biological Diversity, Department of Evolution, Ecology, and Organismal Biology, The Ohio State University, Columbus, OH, United States of America

⁶ Research Laboratory, North Carolina Museum of Natural Sciences, Raleigh, NC, United States of America

⁷ Unit Freshwater habitats, Research Institute for Nature and Forest, Brussels, Belgium

⁸ Estación Biológica de Doñana–CSIC, Sevilla, Spain

⁹ Laboratoire Ecologie et Biologie des Interactions - UMR CNRS 7267, Laboratoire EBI - Equipe Ecologie Evolution Symbiose - Batiment B31, Université de Poitiers, Poitiers, France

¹⁰ Office Français de la Biodiversité, Epinal, France

¹¹ Department of Organismal Biology, Ecology, and Zoo Science, West Liberty University, West Liberty, WV, United States of America

¹² New York State Museum, Albany, NY, United States of America

¹³ Natural Resources Institute Finland, Jyväskylä, Finland

¹⁴ Fisheries Research Station Baden-Württemberg, Langenargen, Germany

¹⁵ Department of Life Sciences and Systems Biology, University of Turin, Turin, Italy

- ¹⁶ Naturalis Biodiversity Center, Leiden, Netherlands
- ¹⁷ Doctoral School of Environmental Science, Hungarian University of Agriculture and Life Sciences, Gödöllő, Hungary
- ¹⁸ Department of Freshwater Fish Ecology, Institute of Aquaculture and Environmental Safety, Hungarian University of Agriculture and Life Sciences, Gödöllő, Hungary
- ¹⁹ School of Biology, Faculty of Biological Science, University of Leeds, Leeds, United Kingdom
- ²⁰ Chair of Aquaculture, Institute of Veterinary Medicine and Animal Sciences, Estonian University of Life Sciences, Tartu, Estonia
- ²¹ Slovak Environment Agency, Banská Bystrica, Slovakia
- ²² Section of Invertebrate Zoology, Carnegie Museum of Natural History, Pittsburgh, PA, United States of America
- ²³ Balearic Biodiversity Centre, Department of Biology, University of the Balearic Islands, Palma, Spain
- ²⁴ Department of Systematic Zoology and Ecology, Eötvös Loránd University, Budapest, Hungary
- ²⁵ Institute of Life Sciences and Technology, Department of Biodiversity, Daugavpils University, Daugavpils, Latvia
- ²⁶ Institute of Biodiversity and Ecosystem Research, Bulgarian Academy of Sciences, Sofia, Bulgaria
- ²⁷ Fish Health Unit, Marine Institute, Galway, Ireland
- ²⁸ Crayfish Research Centre, Institute for Advanced Environmental Research, West University of Timisoara, Timisoara, Romania
- ²⁹ Independent Researcher, Tunja-Boyacá, Colombia
- ³⁰ Instituto de Ciencias Ambientales y Evolutivas, Universidad Austral de Chile, Valdivia, Chile
- ³¹ Scientific and Practical Center for Biological Resources of the National Academy of Science of Belarus, Minsk, Belarus
- ³² Royal British Columbia Museum, Victoria, British Columbia, Canada
- ³³ South African Institute for Aquatic Biodiversity, Makhanda, South Africa
- ³⁴ Water@Leeds, School of Biology, Faculty of Biological Sciences, Leeds, United Kingdom
- ³⁵ Nature Glenelg Trust, South Australia, Australia
- ³⁶ CLLMM Research Centre, Goyder Institute for Water Research, Goolwa, South Australia, Australia
- ³⁷ Department of Hydroecology and Water Protection, Institute for Biological Research “Siniša Stanković”, National Institute of the Republic of Serbia, University of Belgrade, Belgrade, Serbia
- ³⁸ Faculty of Biology, University of Duisburg-Essen, Essen, Germany
- ³⁹ Department of River Ecology and Conservation, Senckenberg Research Institute and Natural History Museum Frankfurt, Gelnhausen, Germany
- ⁴⁰ Branch for Bioresources, Fraunhofer Institute for Molecular Biology and Applied Ecology, Gießen, Germany
- ⁴¹ CAMB, Center for Applied Mathematics and Bioinformatics, Gulf University for Science and Technology, Hawally, Kuwait
- ⁴² Biology Department, College of the Holy Cross, Worcester, MA, United States of America
- ⁴³ Center of Biology, Geosciences and Environmental Education, Faculty of Education, University of West Bohemia, Plzeň, Czech Republic
- ⁴⁴ Faculty of Fisheries, Recep Tayyip Erdogan University, Rize, Turkey
- ⁴⁵ DASARI Research Institute of BioResources, Daejeon, Republic of Korea
- ⁴⁶ Research Center for Endangered Species, National Institute of Ecology, Yeongyang, Republic of Korea
- ⁴⁷ Department Nature and Biodiversity, Brussels Environment, Brussels, Belgium
- ⁴⁸ Institute of Nature Conservation, Polish Academy of Sciences, Kraków, Poland
- ⁴⁹ Biology Program, Glendon College, York University, Toronto, Ontario, Canada
- ⁵⁰ Fisheries Faculty, Firat University, Elazığ, Turkey
- ⁵¹ Ontario Ministry of Natural Resources, Peterborough, Ontario, Canada
- ⁵² Marine and Inland Waters Sciences and Technology Department, Faculty of Fisheries, Ege University, Izmir, Turkey
- ⁵³ Department of Life and Environmental Sciences, Faculty of Science and Technology, Bournemouth University, Poole, Bournemouth, United Kingdom
- ⁵⁴ Department of Ecology and Vertebrate Zoology, Faculty of Biology and Environmental Protection, University of Lodz, Łódź, Poland
- ⁵⁵ Provincial Centre of Environmental Research, Ghent, Belgium
- ⁵⁶ Biology Department, Washington and Lee University, Lexington, VA, United States of America

- ⁵⁷ Department of Environmental and Biological Sciences, University of Eastern Finland, Kuopio, Finland
- ⁵⁸ Department of Aquatic Animal Health, Norwegian Veterinary Institute, Ås, Norway
- ⁵⁹ Biology and Trent School of the Environment, Trent University, Peterborough, Ontario, Canada
- ⁶⁰ Department of Zoology and Fisheries, Faculty of Agrobiological, Food and Natural Resources, Czech University of Life Sciences Prague, Prague, Czech Republic
- ⁶¹ Department of Basic Sciences, Faculty of Fisheries, Muğla Sıtkı Koçman University, Muğla, Turkey
- ⁶² Agro- and Biotechnology, Odisee University of Applied Sciences, Sint-Niklaas, Belgium
- ⁶³ Blattfisch e.U., Wels, Austria
- ⁶⁴ University of Central Florida, Orlando, FL, United States of America
- ⁶⁵ Department of Animal Science, Faculty of Agricultural Sciences, University of Western Macedonia, Florina, Greece
- ⁶⁶ Laboratory of Ichthyology & Fisheries, Faculty of Agriculture, Forestry and Natural Environment, Aristotle University of Thessaloniki, Thessaloniki, Greece
- ⁶⁷ Department of Animal Genetics and Conservation, Institute of Animal Sciences, Warsaw University of Life Sciences, Warsaw, Poland
- ⁶⁸ Department of Aquaculture of Fisheries Faculty, Munzur University, Tunceli, Turkey
- ⁶⁹ Eastern Kentucky University, Richmond, KY, United States of America
- ⁷⁰ Hokkaido Research Organization, Central Fisheries Research Institute, Yoichi Hokkaido, Japan
- ⁷¹ Dipartimento di Biologia, Università di Firenze, Sesto Fiorentino, Italy
- ⁷² Lake Kariba Fisheries Research Institute, Zimbabwe Parks and Wildlife Management Authority, Kariba, Zimbabwe
- ⁷³ USDA Forest Service, Southern Research Station, Center for Bottomland Hardwoods Research, Clemson, SC, United States of America
- ⁷⁴ “Simion Mehedinți - Nature and Sustainable Development” Doctoral School, University of Bucharest, Bucharest, Romania
- ⁷⁵ Department of Computer Science and Information Technology, Faculty of Engineering in Foreign Languages, University Politehnica of Bucharest, Bucharest, Romania
- ⁷⁶ Department of Economic Informatics and Cybernetics, Bucharest University of Economic Studies, Bucharest, Romania
- ⁷⁷ Research and Development Station for Bovine - Arad, Arad, Romania
- ⁷⁸ Information Technology & Communications Department, West University of Timisoara, Timisoara, Romania
- ⁷⁹ Department of Biology, Faculty of Chemistry, Biology, Geography, West University of Timisoara, Timisoara, Romania
- ⁸⁰ Department of Ecology, Faculty of Science, Charles University, Prague, Czech Republic
- * These authors contributed equally to this work.

ABSTRACT

Freshwater crayfish are amongst the largest macroinvertebrates and play a keystone role in the ecosystems they occupy. Understanding the global distribution of these animals is often hindered due to a paucity of distributional data. Additionally, non-native crayfish introductions are becoming more frequent, which can cause severe environmental and economic impacts. Management decisions related to crayfish and their habitats require accurate, up-to-date distribution data and mapping tools. Such data are currently patchily distributed with limited accessibility and are rarely up-to-date. To address these challenges, we developed a versatile *e*-portal to host distributional data of freshwater crayfish and their pathogens (using *Aphanomyces astaci*, the causative agent of the crayfish plague, as the most prominent example). Populated with expert data and operating in near real-time, *World of Crayfish*[™] is a living, publicly available database providing worldwide distributional data sourced by experts in the field. The

database offers open access to the data through specialized standard geospatial services (Web Map Service, Web Feature Service) enabling users to view, embed, and download customizable outputs for various applications. The platform is designed to support technical enhancements in the future, with the potential to eventually incorporate various additional features. This tool serves as a step forward towards a modern era of conservation planning and management of freshwater biodiversity.

Subjects Biodiversity, Biogeography, Bioinformatics, Conservation Biology, Data Science

Keywords *Aphanomyces astaci*, Endangered species, Invasive species, Open data, Astacidae, Cambaridae, Species distribution, Parastacidae

INTRODUCTION

Accurate mapping of species distributions is essential for enhancing and improving conservation efforts and decision-making regarding both native and non-native taxa ([Gonzalez et al., 2023](#)). Data derived models, such as species distribution models, are generally helpful for predicting various scenarios of current and future distributions but require specific expertise and high-quality data for model training and calibration ([Liu et al., 2020](#); [Guareschi et al., 2024](#)). Large, globally open access datasets are a priceless resource for tracking changes in the world's biodiversity ([Liang & Gamarra, 2020](#)). Easy-to use and trustworthy platforms increase the capacity of prompt data collection and adequate assessments of growing pressures on many species in a variety of ecosystems ([Pyšek et al., 2020](#)). Meanwhile, the computation of global data descriptors for geo-physical, climate, and environmental parameters with high-resolution data has increased in availability, with software even designed to provide time series spanning from the past to the present day ([Soto et al., 2023](#)). When high quality environmental and biological data are combined ([Jetz et al., 2019](#)), the potential for highly powerful modeling approaches can be realized ([Domisch, Amatulli & Jetz, 2015](#); [Beck et al., 2018](#); [Kaufman et al., 2020](#)) including, for example, spatially explicit conservation assessment and planning ([Pârvulescu et al., 2020](#); [Ion et al., 2024](#)), predicting future trajectories of biological invasions and monitoring disease outbreaks across river networks ([Satmari et al., 2023](#); [Soto et al., 2023](#)).

The reliability and robustness of modeling approaches highly depend on accurate and precise species distribution data ([Rocchini et al., 2011](#); [Brooks et al., 2019](#); [Li, Bearup & Liao, 2020](#)). Data found in publicly available databases have to be treated with care due to different biases and sources of uncertainties, e.g., the increasing data collection by citizen scientists with varying levels of expertise or variable data-gathering methodologies that challenge the reliability and comparability of the datasets ([Kosmala et al., 2016](#); [Callaghan et al., 2020](#)). Moreover, inaccuracies in species identification and potential disturbances to legally protected or vulnerable species by untrained individuals can compromise data quality and further contribute to conservation concerns, such as the proliferation of pathogens through improper biosecurity during monitoring ([Barve et al., 2011](#); [Robinson et al., 2020](#); [Lipták et al., 2024](#)).

Freshwater crayfish (Crustacea: Decapoda: Astacida) (*sensu Scholtz & Richter, 1995; Crandall & De Grave, 2017*) naturally occur on all continents except Antarctica and continental Africa and include roughly 700 described species (*Crandall & Buhay, 2007; Crandall & De Grave, 2017*) with distinct diversity hotspots in southeastern North America and Australasia (*Lodge et al., 2012*). In freshwater ecosystems, crayfish play an integral role due to their size, longevity, abundance, and omnivorous feeding habits (*Momot, 1995*). Furthermore, crayfish are regarded as a classical conservation conundrum where many are threatened and vulnerable in their native ranges, whereas others are recognized as damaging biological invaders (*Momot, 1995*). Understanding the drivers of this conundrum requires accurate information on their global distributions accompanied by environmental mapping, especially for non-native crayfish, which, once introduced, can become a major pressure on freshwater biota and the functioning of aquatic ecosystems (*Emery-Butcher, Beatty & Robson, 2020*). Crayfish invasions pose a significant threat to native crayfish species due to competition, predation, and the transmission of pathogens. The most prominent pathogen, with severe impacts on Eurasian crayfish populations, is *Aphanomyces astaci* Schikora, the agent responsible for crayfish plague outbreaks in crayfish of non-North American origin (*Chucholl & Schrimpf, 2016; Jussila & Edsman, 2020*). Other crayfish pathogens (e.g., *Grandjean et al., 2019; Stratton et al., 2023; Zingre et al., 2023*) remain much less studied, as their impacts and dispersal have not been notably detrimental to crayfish (*Longshaw, 2011*). As the eradication of non-native crayfish is often deemed impossible (*Lidova et al., 2019; Manfrin et al., 2019*), the prevention of introductions and early detection of introduced non-native crayfish remain the most effective methods to avoiding and mitigating invasions (*Reaser et al., 2019*).

Tracking native and non-native crayfish distributions is therefore of the utmost importance for the conservation of both crayfish and the variety of aquatic ecosystems they inhabit (*Jussila et al., 2021*). Without rapid and accessible communication of field observations, along with geo-spatial descriptive information, effective early management actions are impossible (*Sax & Gaines, 2003; Mcclenachan, Ferretti & Baum, 2012; Salomaki et al., 2020; Miller et al., 2021*). Accurate species identification for many crayfish species, however, remains challenging, particularly in sympatric areas, with expert studies and reports remaining the most trustworthy sources for occurrence data (*Costello, 2009; Costello et al., 2013; Costello & Wicczorek, 2014*). The value of such reliable expert sources may not be maximized unless they are digitized and made available in centralized databases (*Boakes et al., 2010*). Indeed, although the distributions of both native and non-native crayfish as well as the crayfish plague pathogen can be scattered in peer-reviewed publications and other verified resources, there is still a lack of combined, reliable, and publicly accessible data, ultimately limiting the practical applications for researchers and conservation managers. Traditional mapping has been useful for documenting the locations of crayfish species, both native and non-native, and the distribution of different genotypes of the crayfish plague pathogen across Europe (*Kouba, Petrusek & Kozák, 2014; Ungureanu et al., 2020*). However, these maps quickly become outdated, and the large volume of published work, in combination with varying accessibility, makes collating data difficult, time-consuming, and resource intensive (*Thessen, Cui & Mozzherin, 2012*). For instance, a comprehensive

review (Oficialdegui, Sánchez & Clavero, 2020) examined the global spread of *Procambarus clarkii* (Girard, 1852) identifying occurrences in over 40 countries. In the subsequent four years, the documented non-native populations have expanded their ranges and additional invasive populations have emerged in other countries previously deemed free of *P. clarkii* (Lipták et al., 2024).

A comprehensive, large-scale, and amendable database on crayfish distributions should be prioritized to enable quick reporting for accurate assessments of, and predictions about, the evolution of the distributions and the conservation status of these species (Reaser, Frey & Meyers, 2019). This database should facilitate tracking the dynamic ranges of both native and non-native species while being rigorously checked, maintained, and ultimately not subject to inaccuracies and biases of, e.g., citizen science data and non-scientific reports (Troudet et al., 2017; Chandler et al., 2017). Such a database could help scientists and stakeholders make more accurate assessments of the native or non-native status of populations by allowing the identification of possible migration patterns and the most plausible scenarios for the range expansions of some species. Moreover, the efforts of analyzing the spread of pathogens to anticipate the direction and speed of their range expansions and their effects on various species are still in the pioneering stage and require accurate mapping through collaborative efforts among researchers from various fields of expertise (Fišer, 2019; Strand et al., 2019; Marques et al., 2021). For this purpose, and to fill these knowledge gaps in the field of astacology, we introduce the *World of Crayfish*[™] (WoC[™]). This e-portal provides an overview of the worldwide distribution of freshwater and semi-terrestrial crayfish and their most prominent pathogen, *A. astaci* (Martínez-Ríos, Martín-Torrijos & Diéguez-Uribeondo, 2023; Strand et al., 2023), laying the groundwork to address other problematic crustacean pathogens in the near future.

The WoC database and platform provide a valuable resource for addressing current data deficiencies by gathering and curating data from around the world, delivering distributional maps, and centralizing datasets. In addition, the platform provides an alternative repository for datasets from new publications or indeed prior to publication by offering a unique accession code for each available record. In doing so, WoC overcomes the publication lag time in reporting occurrence data. As WoC accumulates larger volumes of both temporal and spatial data, it will become increasingly relevant for agencies (e.g., the *International Union for Conservation of Nature*, *CABI Compendium*, *European Alien Species Information Network*) responsible for assessing and updating the conservation status of crayfish species and monitoring the changing distributions of native and non-native crayfish. Moreover, WoC is built to enable the implementation of additional features and improvements as data availability increases, opening new opportunities for state-of-the-art approaches to ecological modeling of crayfish and crayfish plague occurrences. This initiative is expected to boost and assist research and the publication of faunistic-focused studies on crayfish contributing to their conservation and management.

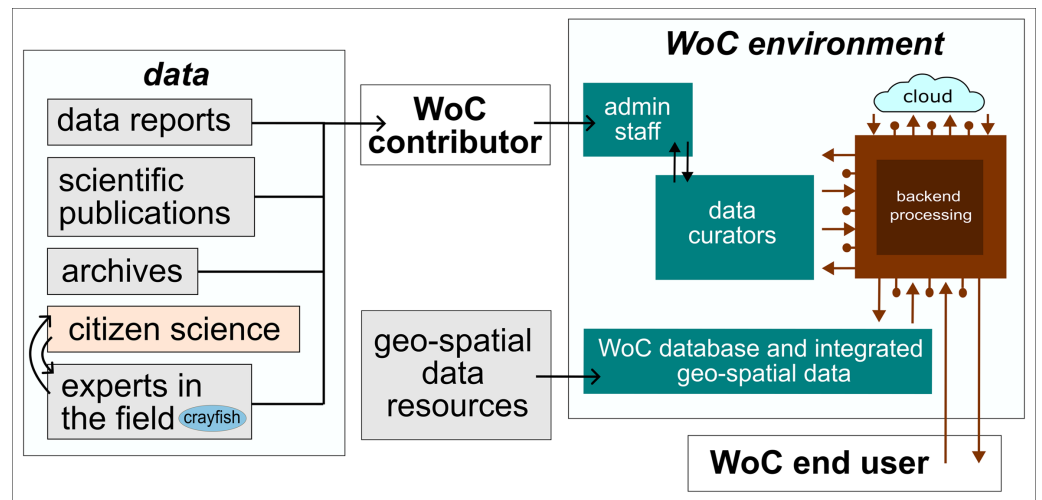


Figure 1 Logical workflow. Schematic representation of the logical workflow in and around the *World of Crayfish* environment, detailing potential data origins and how the data is processed by WoC before being provided to the end user. The figure was created using Inkscape (<https://inkscape.org>).

Full-size DOI: 10.7717/peerj.18229/fig-1

METHODS

Description

World of Crayfish is a platform that can be accessed at <https://world.crayfish.ro/>. The platform has an interface that welcomes the user with a brief description of its purpose, along with an introduction to the team behind the project and video instructions to help users understand and navigate the site. New data can be submitted through a downloadable EXCEL template accompanied by an instruction guide, enabling the platform to host continuously updated maps. Each data contributor can choose a restriction level prior to submitting new records to WoC. This feature permits that, if a high level of protection (e.g., threatened status of a particular crayfish species or distribution data prior publication) is selected, the exact location (and associated data) is hidden for non-registered users, but those records still contribute to the coarser-scale grid map visualization to ensure the best coverage of a species distribution. A technical review of new datasets is conducted by administrators using an offline preliminary check of the locations' accuracy (and other additional provided information) in accordance with the original sources. The logical workflow is presented in Fig. 1.

Database

The database is structured in a single table containing the information, formatted in the same manner as the EXCEL template file for data contributors. The database fields are structured in five sections (Table 1). The first section is dedicated to the source of information, including the Digital Object Identifier (DOI), accompanied by the URL where the article/dataset can be found (if a DOI is not available) and the citation reference in APA format. The second section consists of location data (coordinates: X–latitude and Y–longitude, in decimal degrees, WGS84 datum), accompanied by

Table 1 The *World of Crayfish* database fields' structure, also available as a template for contributors (NRU –non-registered users, and RU –registered users).

Section	Title	Brief description	Available for	
			NRU	RU
Source information	DOI	Digital object identifier, a mandatory field (if available).	Yes	Yes
	URL	Uniform Resource Locator, the address of a given resource on the Web.	Yes	Yes
	Citation	Full reference for the source (for articles), APA format. For unpublished data, the contributors may ask for unique WoC database identifier.	Yes	Yes
Geolocation	X	Latitude, in decimal degree, WGS 84 datum.	No	Yes
	Y	Longitude, in decimal degree, WGS 84 datum.	No	Yes
	Accuracy	Specifies how precise the provided coordinates are in relation to the place of field observation. High: data sourced from field records, maps at a hydrographic level, toponymy with high detail. Low: data sourced from continental or national grid systems, estimated locations based on toponymy with low detail.	No	Yes
Crayfish	Crayfish scientific name	A mandatory field for the scientific name of the observed crayfish species. Exceptionally empty, when a record of <i>Aphanomyces astaci</i> without host (<i>i.e.</i> , by eDNA detection) is stored.	Yes	Yes
	Status	Native: a crayfish species that naturally occurs in a specific region due to natural evolution over time. Non-native: a crayfish species (or associated pathogen) that has arrived facilitated by non-natural actions in a region where it does not belong due to natural evolution over time. Introduced: a crayfish species (or associated pathogen) that has arrived facilitated by human-mediated translocation. Type locality: if indexing the paper in which a species has been initially described. These categories in the table are not value-laden.	Yes	Yes
	Year of observation	The year when the observation of the crayfish species was made.	Yes	Yes
	NCBI COI accession code	The accession code in NCBI's GenBank for COI sequence if such data is available. Comma separated, if multiple.	No	Yes
	NCBI 16S accession code	The accession code in NCBI's GenBank for 16S sequence if such data is available. Comma separated, if multiple.	No	Yes
	NCBI SRA accession code	The Sequence Read Archive in NCBI's GenBank if such data is available. Comma separated, if multiple.	No	Yes
	Claim extinction	If confident that a crayfish population has completely disappeared this option is available. This selection will discard the spot from the time series maps starting with its year of record.	No	Yes

(continued on next page)

Table 1 (continued)

Section	Title	Brief description	Available for	
			NRU	RU
Associated pathogens & symbionts	Pathogen/symbiont present	The scientific name of a crayfish associated pathogen (<i>i.e.</i> , <i>A. astaci</i>) or symbiont (<i>i.e.</i> , <i>Branchiobdella</i> sp.), if any, on a crayfish specimen (data stored in Crayfish section).	Yes	Yes
	Pathogen/symbiont detection method	Contributor declaration of the method used for detection of the pathogen/symbiont: Molecular/Microscopic/eDNA/any other.	Yes	Yes
	Pathogen/symbiont genotyping method	If available: Chitinase sequencing/Microsatellites/mtDNA sequencing/AFLP/RFLP/RAPD/Anonymous nuclear markers. Comma separated, if multiple.	Yes	Yes
	Genotype group	If available: A/B/D/E/Up/other described.	Yes	Yes
	Haplotype	If available: d1/d2/other described.	Yes	Yes
	Year of observation	The year when the samples were taken.	Yes	Yes
Additional information	Comments	Any optional additional information that might be worth mentioning.	Yes	Yes
	Confidentiality level	The degree of public availability that the contributor has chosen for the data. No restrictions: data will be displayed with the exact location for all users. Regular restrictions: 20 km hexagonal shape displayed for NRU, exact location display for RU. High restrictions: data displayed in a 20 km hexagonal shape for all users.		
	Contributor	The name of the contributor holder to the database for a respective record.	Yes	Yes

accuracy (ensuring that the provided locations correspond to the place of a field observation). The third section centralizes the scientific species name (according to the taxonomy available in *World Register of Marine Species*, WoRMS, accessed on 14.03.2024, <https://www.marinespecies.org/>), its status at the locality (native vs. non-native or introduced), based on expert assessment in the original source of data records (*sensu Soto et al., 2024*), and a specific “type locality” mark, if indexing the paper in which a species has been originally described, year of observation, and a set of *National Center for Biotechnology Information* (NCBI) GenBank accession codes, if available (COI, 16S, SRA). Where there is a high level of confidence that a crayfish population has completely disappeared, this section can mark “extinct” which will discard the spot from the time series maps starting with the year of a scientifically documented population extinction record. The fourth section is dedicated to recording details of the crayfish associated pathogens or symbionts (if any) identified at the specified coordinates of the crayfish record, alongside pathogen detection and genotyping methods, and eventual genotype and haplotype classification. If detection of the pathogen or symbiont was confirmed by environmental DNA analysis, then sample coordinates are registered instead of a crayfish host. Finally, the fifth section provides any additional information that might be worth mentioning, including the contributor’s name and a confidentiality level that may establish restrictions for data. The confidentiality level will be displayed and downloaded with the associated location for users.

Each record is stored under a unique ID. The EXCEL template has a corresponding table in the *PostgreSQL/PostGIS* database allowing new contributions to be added easily. The corresponding database table has the same attributes as the EXCEL table but also a *PostGIS* specific geometry column so that the location data is easily managed by software. The data from the database is then read by the QGIS Server and served through the WoC platform.

Administrators and users

The user registration system (upstreamed in the Open-Source code) was developed so that a new user can apply, and receive access approval, based on a specific workflow and requirements setup in the administration side of the platform. New users are reviewed, approved and assigned custom security privileges by the platform administrators who get notified by e-mail of the new sign-up. The platform has an administrator interface that is used to assign granular security privileges for any users: view/edit privileges at project/theme level, layer level, column level or feature level. Feature level permissions are assigned using two kinds of filters: data source level - SQL “WHERE” filters or QGIS Server level - QGIS Expressions. Therefore, the distribution maps’ view is layered with two levels of access: (i) non-registered users (NRU), and (ii) registered users (RU). New users are accepted based on a declaration that can attest to professional interest.

Display

From the database, the platform displays the information about the selected taxon using *OpenStreetMap* (<https://www.openstreetmap.org/>) as a basemap. For NRU, records are displayed as hexagons, with each edge measuring 20 km. Crayfish species occurrences

are aggregated per cell to protect the information on the exact location of the crayfish for conservation purposes. We generated a global hexagonal cell grid using the QGIS platform “Create Grid” algorithm available in the QGIS Processing framework and saved it as a distinct table. To visually distinguish the different occurrences per species, the Jenks natural breaks classification method was used for grid display. For each species, we correlated the number of occurrences with the opacity value for each cell with a minimum of one occurrence. The opacity scale ranges from 20 (partially opaque cell) to 100 (fully opaque cell). In contrast, RU, once logged in, may also see a dotted map display with the exact crayfish locations shown on the map according to the coordinates stored in the database. One or multiple taxa can be inspected simultaneously and will be automatically allocated different colors, either with hexagons or dot shapes displayed. *Aphanomyces astaci* records can be displayed individually, or together with those of crayfish species.

Attribute data

From the WoC database, a set of associated data with the record(s) in the hexagon (for NRU) or dot (for RU), is displayed. Attribute data lists species names, status (Native/Non-native), number of observations in the selected hexagon (for NRU), year of observation, bibliographic references, and the names of the persons who indexed the data in WoC. The bibliographic reference, linked to a DOI or similar URL, will send the user directly to the source paper. Using specific geospatial standards, the attribution of information for each geospatial feature is accessed using a Web Map Service GetFeatureInfo request.

Export

The platform can generate maps and tables to be exported, available for the RU only, listing: GPS coordinates in WGS84 format (if the taxon is not specifically restricted, at the contributor’s request), accuracy of the localities, the countries in which the species is present, basic statistics on the number of records, and the related source literature. Also, the platform can be used as an alternative to dataset repositories for new publications as it provides unique, identifiable, searchable, and sharable ID (accession code) for each record. The user can access the data through standard geospatial services—OGC (Open Geospatial Consortium) services: WMS (Web Map Service) and WFS (Web Feature Service). Any RU has access to the data through the WFS endpoint according to their privileges, providing the possibilities of download, visualization and embedding into other applications (e.g., QGIS, ArcGIS, Geoserver). For instance, users can access the WMS at: <https://map.crayfish.ro/ows/crayfish?SERVICE=WMS&REQUEST=GetCapabilities>.

Data records

The key features offered by WoC are (1) the compilation of global records into a single accessible platform, enabling users to gain a comprehensive understanding of the distributions of many species of an important freshwater taxonomic group, and (2) the ability to grow by serving as a data repository for newly published studies on freshwater crayfish or the crayfish plague pathogen. Here we present an informative overview of the database at the time of the publication (Fig. 2, and Tables S1–S3), with 105,611 records indexed from 427 taxa (species, subspecies or species complex; see Table S1). Of these

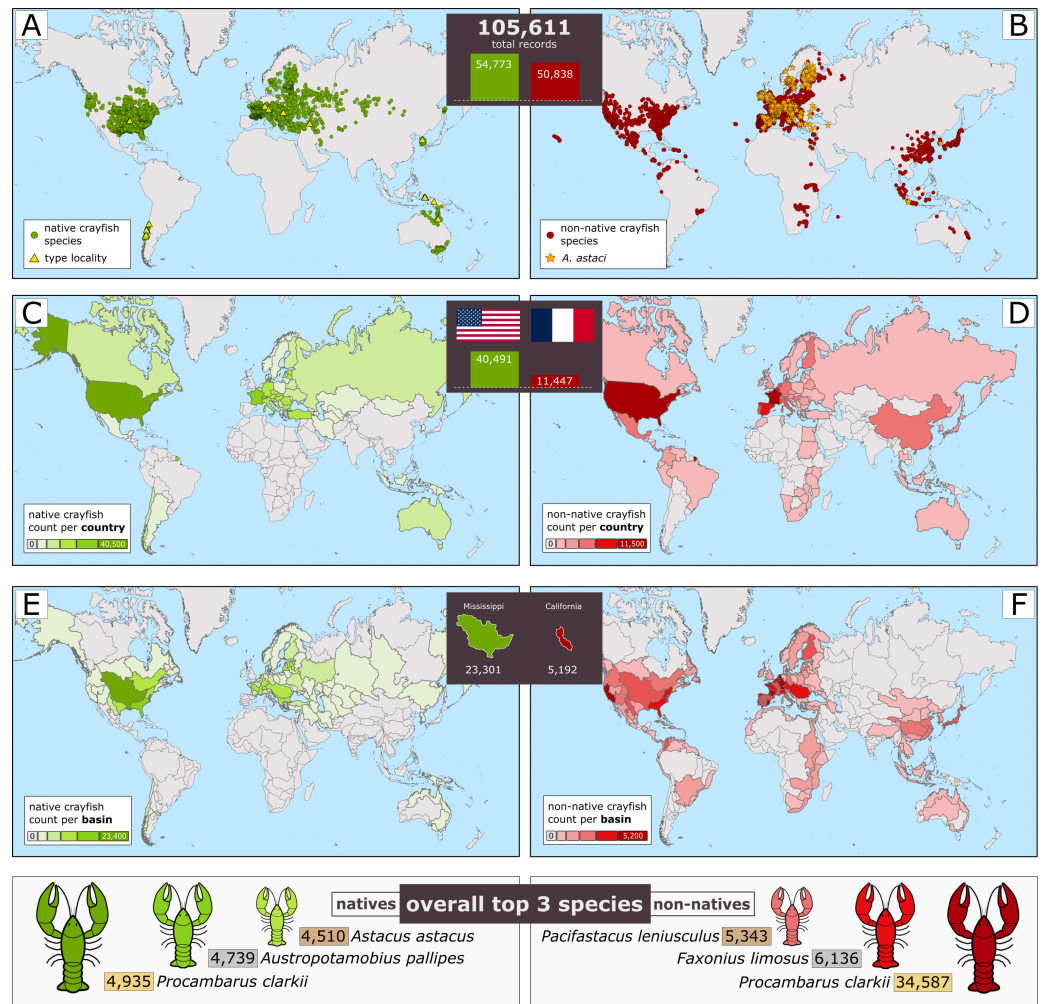


Figure 2 Overview of the collected data in the *World of Crayfish* platform, and various centralisation of records of natives *versus* non-native (introduced status included). (A–B) Crayfish species records at continental level (type locality and *Aphanomyces astaci* highlighted), (C–D) country level record counts, and (E–F) major hydrographic basins record counts. The lower panel integrates data for the best-represented species. The collage was created in Inkscape (<https://inkscape.org>) using maps generated in ArcGIS Pro (ESRI, Redlands) with freely available basemap layers: (A–B) world continents from ESRI (https://services.arcgis.com/P3ePLMYs2RVChkJx/arcgis/rest/services/World_Continents/FeatureServer), (C–D) administrative boundaries at country level from EuroGeographics (<https://ec.europa.eu/eurostat/web/gisco/geodata/administrative-units/countries>), and (E–F) major hydrological basins from the Food and Agriculture Organization of the United Nations (<https://data.apps.fao.org/catalog/iso/7707086d-af3c-41cc-8aa5-323d8609b2d1>). Crayfish silhouettes were drawn by Lucian Pârvolescu.

Full-size DOI: 10.7717/peerj.18229/fig-2

records, 72.9% ($n = 77,062$) are of high geolocation accuracy. In the current dataset, the North American continent has the highest diversity (including non-native species) with 390 taxa indexed and 51,940 stored records (49.2%). For a detailed count per country, we refer readers to [Table S2](#). The Mississippi - Missouri River Basin holds almost one quarter of the global occurrence records (23,301; 22.1%; [Table S3](#)). Almost half (48.1%) of the total

observations currently held by WoC ($n = 50,838$) are ascribed to non-native species, with the most widely reported non-native species being *P. clarkii* with 34,587 records (32.8%) across six continents. The second most reported species outside its native range is *Faxonius limosus* (Rafinesque, 1817) with 6,136 records (5.8%). Currently, there are 428 data records associated with *A. astaci*, which are mostly spread over continental Europe.

With the severe decline of native crayfish populations and the rapid spread of non-native crayfish (Richman et al., 2015), WoC is expected to be the go-to access point for the rapid and reliable interpretation of spatial and temporal dynamics of crayfish species globally. The easy access to contributing references is helpful not only for new studies, but also for making the data from existing scientific publications available to a broader audience. Moreover, the contribution of international collaborators allows WoC to reach crayfish gray literature, often written in local languages and concerning local context (Hannah et al., 2024). The accessibility and utilization of gray literature, although often neglected, holds paramount importance in nature conservation (Amano et al., 2021; Amano et al., 2023). The platform offers the possibility to revise one or multiple indexed locations to list a population as extinct, with 126 such situations already indexed. This function allows for time series interruptions if new data suggest that populations from a previously published resource have disappeared, indicating a potential focal point for various ecological pressures (for example, habitat degradation or destruction). In contrast, once a regular location point is entered, it remains “forever” visible in the time series from the date of the original observation stored in the database.

By their very nature, global-scale analyses require large datasets, but distributional data are of limited value if not associated with geospatial ecological variables specifically designed to describe the hydrographic networks (Domisch, Amatulli & Jetz, 2015). State-of-the-art modeling approaches offer a means to explore and uncover previously unrecognized ecological relationships, thereby reducing uncertainty and validating the significance of outputs (Shen et al., 2023). The WoC platform has been designed to address these challenges by storing locations based on the accuracy of each data point, ensuring high-quality representation of the water bodies where the crayfish reside. This approach enables us to filter data appropriately for different modeling purposes. The platform could provide opportunities to assess, for instance, habitat selection patterns and post-glacial migration routes taken by crayfish species and identify the glacial refugia these crayfish may have used during the last Ice Age; which can be useful for understanding modern day distributions and predicting future changes in distributions in relation to climate change and other environmental variables (Guiasu, Barr & Dunham, 1996; Guiasu & Labib, 2021). We advocate for the use of geospatial data designed to describe dendritic river networks instead of landscape-based approaches, as they provide a more ecologically relevant representation of crayfish habitats (Fetzner & Crandall, 2003). The next level in the development of the WoC platform is to add a feature whereby registered users will be able to download customizable datasets to support their modeling procedures.

Technical validation

The ability to visualize geographic ranges of multiple species and their environmental conditions is a critical resource for ecological and conservation research aiming to assess an organism's response to change (Villero *et al.*, 2017). Centralized resources will improve capacity for spatially explicit management and policy decision-making regarding endemic, threatened, and non-native crayfish (Taylor *et al.*, 2019). It is important to ensure that such data are based on rigorous investigations to avoid potential errors and inaccuracies. The distinctions and boundaries between native and non-native ranges, particularly in areas where these ranges are adjacent to each other and not separated by any obvious environmental barriers, can often be difficult to establish and decisions on the native or non-native status of species can be subjective (Pereyra & Guiaşu, 2020). Comprehensive, regularly updated, and professionally curated datasets on the distributions of species hold the promise of more accurate diagnoses regarding the status of these species and the evolution of their ranges over time. Raw data, such as those obtained from citizen science online databases, are generally useful, but need expert validation as they may be prone to errors resulting from taxonomic confusion, species misidentification, and mistakes in recording locations, among others (Clare *et al.*, 2019; Lipták *et al.*, 2024). In the particular case of crayfish, expert-validated data are more likely to be accurate and reliable since they are typically subjected to rigorous taxonomic scrutiny, which is essential for accurate species identification (Jiménez-Valverde, Lobo & Hortal, 2008). In some cases, additional molecular analyses are used to confirm taxonomic identifications, further increasing the accuracy of the data (Bystriakova *et al.*, 2012). Nevertheless, there are also some disadvantages associated with data from published sources as, for example, the lag time between data being obtained and published may be slow, limiting its usefulness for time-sensitive research. Data from published sources can also be difficult to centralize due to the diverse publication access policies of different journals and the heterogeneity of databasing formats (Reichman, Jones & Schildhauer, 2011).

WoC's maps provide an advantage over drawing from the literature by eliminating the time-consuming, and often repeated, effort for every new study. Our indexed data are delivered in a unitary format, with emphasis on geographic locations in WGS84 datum and validated accuracy, which greatly eases and streamlines the processes required for modeling input data. The known level of accuracy allows data filtering, saving time, and enabling quality datasets. It is important to note that, when visualizing large-scale distribution maps, accuracy is not always prioritized; hence, our map can display all levels of data accuracy. We provide a confidence rating through the accuracy attribute in our downloadable datasets, allowing modelers to make informed decisions on the preciseness of the data they use. When developing models, the presence of redundancy and imbalances in sampling can impact the overall quality of the model. Therefore, we recommend that researchers consider spatial re-sampling to ensure uniform geographical coverage in their selected areas (Guisan & Zimmermann, 2000). Species-associated data issues can also be related not only to taxonomic errors (Meier & Dikow, 2004) but also to inaccurate or incomplete spatial and temporal information (Meyer, Weigelt & Kreft, 2016). While misidentification should be a lesser issue for data from peer-reviewed articles, spatial errors

can occur and need clarification (Graham et al., 2008; Führding-Potschkat, Kreft & Ickert-Bond, 2022). One of the most frequent issues observed while indexing papers for WoC was the insufficient standardization of spatial data formatting and overall dataset heterogeneity. When coordinates of locations were supplied in publications (usually as supplementary material) and not just maps, these were sometimes lacking important information like the type of geographic coordinates used or zones for Universal Transverse Mercator (UTM) grid derived systems. These situations generate confusion for most users without GIS training. A lack of more detailed and precise information on the coordinate reference systems may lead to significant positional errors with a shift from the original position between zero and more than 5,000 m (Wieczorek, Guo & Hijmans, 2004; Guralnick et al., 2006). Even though a high correlation between models derived from the *Global Biodiversity Information Facility* (GBIF) and those from expert data is often found (Führding-Potschkat, Kreft & Ickert-Bond, 2022), expert data did not require processing. While possibly true for some taxa, assembling several expert datasets for crayfish still requires some degree of homogenization and a comprehensive review for completeness.

Finally, there is a concerning trend of declining interest in faunistic studies at the level of high-impact scientific journals (Ejsmont-Karabin, 2019). Faunistic studies may be of more interest to some governmental organizations, which only target certain species, such as those listed in legislation either because they may be vulnerable or endangered or because they may be regarded as invasive. This potential bias leaves a large gap in scientific knowledge and the conservation of biodiversity at a global level, since most other species are largely ignored (Valdecasas & Camacho, 2003; Rodríguez et al., 2015). Data curation with the aid of automated information retrieval from published literature is a promising avenue for near real-time databasing (Kopperud, Lidgard & Liow, 2022). Screening tools and automatic data collection from the scientific literature based on natural language processing to extract the locations of crayfish species with text-mined occurrences, and solving language barriers by machine linguistic translation, are essential for sourcing large scale biodiversity data (Amano et al., 2023; Hannah et al., 2024). In addition, features for automated population genetics and phylogenetic analyses are plausible, based on freely accessible data from public genetic databases and popular open-source packages implemented using the R programming language (RCoreTeam, 2024). All these features may represent future opportunities to improve the WoC platform and reinvigorate the interest for faunistic studies not only on crayfish, but also on a variety of other taxa.

Usage notes

World of Crayfish itself is a repository database. In addition to the repository files, these data are also available *via* the interactive web platform (<https://world.crayfish.ro/>). Site access is free, however exact location of crayfish species is restricted to prevent commercial exploitation of sensitive species. The ‘fairness’ of WoC has been assessed using FairShake, which provided a comprehensive evaluation confirming that the datasets adhere to the FAIR principles (Wilkinson et al., 2016; Barker et al., 2022) through rigorous metrics and criteria, ensuring high standards of data management and usability. The WoC is a word and figurative trademark, pending registration (No. M2024/08475 of 16.09.2024) at the

Romanian National Office for Intellectual Property, at the time of this paper's publication. The request for trademark award is done under Class 42 of the Nice Classification (*World Intellectual Property Organization, 2022*). The award of the national trademark certification will be followed with a request for international protection at the World Intellectual Property Office in accordance with the Madrid System. However, we encourage citation of those sources associated with any record in WoC, and the WoC platform should be cited as the tool for delivering multi-source compilations and various outputs.

Code availability

WoC was developed using Open-Source software g3w-suite (<https://github.com/g3w-suite/>), a Django based QGIS platform and PostgreSQL/Postgis. The code written for WoC (e.g., <https://github.com/g3w-suite/g3w-admin/pull/610>) has been upstreamed to allow broader access and to reduce the maintenance burden.

CONCLUSIONS

The primary product offered by WoC is knowledge, facilitated through machine-driven querying of scientific data, aligning with the Digital: Green: Nature trend. Looking ahead, this project has the potential to elevate the conceptual use and utility of biodiversity databases. WoC envisions a platform populated exclusively by experts and their study data, developed with the highest standards and using the most advanced technologies, fostering interdisciplinarity between biological sciences and Geographic Information Systems.

To date, 98.5% of the data hosted on WoC is sourced from scientific papers, data reports, and museum databases. Additionally, WoC offers a repository function for further publication with 1,444 (1.5%) records from otherwise unpublished datasets. The database also provides, where available, the specific *GenBank* accession codes for the most common DNA sequences from genetic studies on crayfish, with 2,065 for CO1, 1,375 for 16S, and 15 SRA records already being available in WoC. The platform also features a function to filter species records based on the status attribute, listed as “type locality”. This functionality, which presently returns 16 type localities, allows users to efficiently access hard-to-find information, such as original formal species descriptions from the scientific literature, and visualize this information on a map. To protect sensitive species information, the exact geographic location of a species is only available to RUs, whereas NRUs can only view the records within hexagonal areas.

Crayfish exhibit a distinctive ecology, inhabiting a wide range of aquatic and semi-terrestrial habitats (*Neculae et al., 2024*). The distributional data hosted by WoC, combined with geospatial data specifically adapted to this diversity of habitats (e.g., *Pârvulescu et al., 2016*; *Şandric et al., 2019*), will improve analyses of the distributional patterns of crayfish. The future integration of statistical and data processing methods will significantly enhance our platform's capabilities and further biogeographical research. Additionally, we plan to improve user accessibility and interaction through advanced IT programming, culminating in an Artificial Intelligence interaction across various levels (data collection and curation, results interpretation, reporting), making it easier for users to navigate, analyse, and utilize the information available on the platform. With certain future potential, WoC is the first

global platform created for scientists, society, and stakeholders, specifically to support the conservation and management of crayfish as an important and historically under-resourced taxon.

ACKNOWLEDGEMENTS

The authors wish to extend their gratitude, in advance, to the forthcoming contributors who will generously contribute to the growth of WoC. The invaluable support from these data providers is essential, as their contributions are instrumental for enhancing the richness and value of this platform. We appreciate the comments provided from three anonymous reviewers which served to improve the manuscript.

ADDITIONAL INFORMATION AND DECLARATIONS

Funding

This work was supported by (1) the West University of Timisoara through the U InnoVaTe programme, via an UIVT Mature grant awarded to the, World of Crayfish (WoC1.0)” project in May 2023, and (2) the Ministry of Research, Innovation and Digitization, CNCS/CCCDI–UEFISCDI, within the PNCDI III programme (No. PN-III-P4-ID-PCE-2020-1187). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Grant Disclosures

The following grant information was disclosed by the authors:

West University of Timisoara through the U InnoVaTe programme.

Ministry of Research, Innovation and Digitization, CNCS/CCCDI–UEFISCDI, within the PNCDI III programme: No. PN-III-P4-ID-PCE-2020-1187.

Competing Interests

The authors declare there are no competing interests.

Author Contributions

- Mihaela C. Ion conceived and designed the experiments, performed the experiments, analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the article, data curation, and approved the final draft.
- Caitlin C. Bloomer conceived and designed the experiments, performed the experiments, authored or reviewed drafts of the article, data curation, and approved the final draft.
- Tudor I. Băräscu conceived and designed the experiments, performed the experiments, authored or reviewed drafts of the article, iT support and development, and approved the final draft.
- Francisco J. Oficialdegui conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Nathaniel F. Shoobs conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.

- Bronwyn W. Williams conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Kevin Scheers conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Miguel Clavero conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Frédéric Grandjean conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Marc Collas conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Thomas Baudry conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Zachary Loughman conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Jeremy J. Wright conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Timo J. Ruokonen conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Christoph Chucholl conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Simone Guareschi conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Bram Koesse conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Zsombor M. Banyai conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- James Hodson conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Margo Hurt conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Katrin Kaldre conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Boris Lipták conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- James W. Fetzner conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Tommaso Cancellario conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- András Weiperth conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Janis Birzaks conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.

- Teodora Trichkova conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Milcho Todorov conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Maksims Balalaikins conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Bogna Griffin conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Olga N. Petko conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Ada Acevedo-Alonso conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Guillermo D'Elía conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Karolina Śliwińska conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Anatoly Alekhnovich conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Henry Choong conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Josie South conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Nick Whiterod conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Katarina Zorić conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Peter Haase conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Ismael Soto conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Daniel J. Brady conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Phillip J. Haubrock conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Pedro J. Torres conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Denis Şadrin conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Pavel Vlach conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Cüneyt Kaya conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.

- Sang Woo Jung conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Jin-Young Kim conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Xavier H.C. Vermeersch conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Maciej Bonk conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Radu Guiășu conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Muzaffer M. Harlioğlu conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Jane Devlin conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Irmak Kurtul conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Dagmara Błońska conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Pieter Boets conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Hossein Masigol conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Paul R. Cabe conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Japo Jussila conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Trude Vrålstad conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- David V. Beresford conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Scott M. Reid conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Jiří Patoka conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- David A. Strand conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Ali S. Tarkan conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Frédérique Steen conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Thomas Abeel conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.

- Matthew Harwood conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Samuel Auer conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Sandor Kelly conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Ioannis A. Giantsis conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Rafał Maciaszek conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Maria V. Alvanou conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Önder Aksu conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- David M. Hayes conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Tadashi Kawai conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Elena Tricarico conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Adroit Chakandinakira conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Zanethia C. Barnett conceived and designed the experiments, authored or reviewed drafts of the article, database, and approved the final draft.
- Ștefan G. Kudor conceived and designed the experiments, performed the experiments, authored or reviewed drafts of the article, data curation, and approved the final draft.
- Andreea E. Beda conceived and designed the experiments, authored or reviewed drafts of the article, iT support and development, and approved the final draft.
- Lucian Vilcea conceived and designed the experiments, performed the experiments, authored or reviewed drafts of the article, iT support and development, and approved the final draft.
- Alexandru E. Mizeranschi conceived and designed the experiments, authored or reviewed drafts of the article, literature review, and approved the final draft.
- Marian Neagul conceived and designed the experiments, authored or reviewed drafts of the article, iT support and development, and approved the final draft.
- Anton Licz conceived and designed the experiments, authored or reviewed drafts of the article, iT support and development, and approved the final draft.
- Andra D. Cotoarbă conceived and designed the experiments, authored or reviewed drafts of the article, and approved the final draft.
- Adam Petrussek conceived and designed the experiments, authored or reviewed drafts of the article, literature review, and approved the final draft.
- Antonín Kouba conceived and designed the experiments, authored or reviewed drafts of the article, literature review, and approved the final draft.

- Christopher A. Taylor conceived and designed the experiments, authored or reviewed drafts of the article, project supervision, coordinate data collection, facilitate collaborations, and approved the final draft.
- Lucian Pârvulescu conceived and designed the experiments, performed the experiments, analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the article, project management, coordinate data collection, facilitate collaborations, and approved the final draft.

Patent Disclosures

The following patent dependencies were disclosed by the authors:

The World of Crayfish (WoC) trademark is pending registration at the Romanian National Office for Intellectual Property. The request for trademark award is done under Class 42 of the Nice Classification (World Intellectual Property Organization, 2022). The award of the national trademark certification will be followed with a request for international protection at the World Intellectual Property Office in accordance with the Madrid System.

Data Availability

The following information was supplied regarding data availability:

The data is available in the [Supplemental Files](#).

Supplemental Information

Supplemental information for this article can be found online at <http://dx.doi.org/10.7717/peerj.18229#supplemental-information>.

REFERENCES

- Amano T, Berdejo-Espinola V, Akasaka M, De Andrade Junior MAU, Blaise N, Checco J, Çilingir FG, Citegetse G, Corella Tor M, Drobniak SM, Giakoumi S, Golivets M, Ion MC, Jara-Díaz JP, Katayose R, Lasmana FPS, Lin HY, Lopez E, Mikula P, Morales-Barquero L, Mupepele AC, Narváez-Gómez JP, Nguyen TH, Lisboa SN, Nuñez MA, Pavón-Jordán D, Pottier P, Prescott GW, Samad F, Šćiban M, Seo HM, Shinoda Y, Vajna F, Vozykova S, Walsh JC, Wee AKS, Xiao H, Zamora-Gutierrez V. 2023. The role of non-English-language science in informing national biodiversity assessments. *Nature Sustainability* 6(7):845–854 DOI [10.1038/s41893-023-01087-8](https://doi.org/10.1038/s41893-023-01087-8).
- Amano T, Berdejo-Espinola V, Christie AP, Willott K, Akasaka M, Baldi A, Berthinussen A, Bertolino S, Bladon AJ, Chen M, Choi CY, Kharrat MBD, De Oliveira LG, Farhat P, Golivets M, Aranzamendi NH, Jantke K, Kajzer-Bonk J, CiselKemahli Aytekin M, Khorozyan I, Kito K, Konno K, Lin DL, Littlewood N, Liu Y, Liu Y, Loretto MC, Marconi V, Martin PA, Morgan WH, Narvaez-Gomez JP, Negret PJ, Nourani E, Ochoa Quintero JM, Ockendon N, Oh RRY, Petrovan SO, Piovezan-Borges AC, Pollet IL, Ramos DL, Reboredo Segovia AL, Nayelli Rivera-Villanueva A, Rocha R, Rouyer MM, Sainsbury KA, Schuster R, Schwab D, Sekercioglu CH, Seo HM, Shackelford G, Shinoda Y, Smith RK, Tao SD, Tsai MS,

- Tyler EHM, Vajna F, Valdebenito JO, Vozykova S, Waryszak P, Zamora-Gutierrez V, Zenni RD, Zhou W, Sutherland WJ. 2021. Tapping into non-English-language science for the conservation of global biodiversity. *PLOS Biology* 19:e3001296 DOI 10.1371/JOURNAL.PBIO.3001296.
- Barker M, Chue Hong NP, Katz DS, Lamprecht AL, Martinez-Ortiz C, Psomopoulos F, Harrow J, Castro LJ, Gruenpeter M, Martinez PA, Honeyman T. 2022. Introducing the FAIR Principles for research software. *Scientific Data* 9:622 DOI 10.1038/s41597-022-01710-x.
- Barve N, Barve V, Jiménez-Valverde A, Lira-Noriega A, Maher SP, Peterson AT, Soberón J, Villalobos F. 2011. The crucial role of the accessible area in ecological niche modeling and species distribution modeling. *Ecological Modelling* 222:1810–1819 DOI 10.1016/J.ECOLMODEL.2011.02.011.
- Beck HE, Zimmermann NE, McVicar TR, Vergopolan N, Berg A, Wood EF. 2018. Present and future köppen-Geiger climate classification maps at 1-km resolution. *Scientific Data* 5:180214 DOI 10.1038/sdata.2018.214.
- Boakes EH, McGowan PJK, Fuller RA, Chang-Qing D, Clark NE, O'Connor K, Mace GM. 2010. Distorted views of biodiversity: spatial and temporal bias in species occurrence data. *PLOS Biology* 8:e1000385 DOI 10.1371/JOURNAL.PBIO.1000385.
- Brooks TM, Pimm SL, Akçakaya HR, Buchanan GM, Butchart SHM, Foden W, Hilton-Taylor C, Hoffmann M, Jenkins CN, Joppa L, Li BV, Menon V, Ocampo-Peñuela N, Rondinini C. 2019. Measuring terrestrial Area of Habitat (AOH) and its utility for the IUCN Red List. *Trends in Ecology and Evolution* 34:977–986 DOI 10.1016/j.tree.2019.06.009.
- Bystriakova N, Peregrym M, Erkens RHJ, Bezsmertna O, Harald S. 2012. Sampling bias in geographic and environmental space and its effect on the predictive power of species distribution models. *Systematics and Biodiversity* 10:305–315 DOI 10.1080/14772000.2012.705357.
- Callaghan CT, Roberts JD, Poore AGB, Alford RA, Cogger H, Rowley JLL. 2020. Citizen science data accurately predicts expert-derived species richness at a continental scale when sampling thresholds are met. *Biodiversity and Conservation* 29:1323–1337 DOI 10.1007/s10531-020-01937-3.
- Chandler M, See L, Copas K, Bonde AMZ, López BC, Danielsen F, Legind JK, Masinde S, Miller-Rushing AJ, Newman G, Rosemartin A, Turak E. 2017. Contribution of citizen science towards international biodiversity monitoring. *Biological Conservation* 213:280–294 DOI 10.1016/J.BIOCON.2016.09.004.
- Chucholl C, Schrimpf A. 2016. The decline of endangered stone crayfish (*Austropotamobius torrentium*) in southern Germany is related to the spread of invasive alien species and land-use change. *Aquatic Conservation: Marine and Freshwater Ecosystems* 26:44–56 DOI 10.1002/aqc.2568.
- Clare JDJ, Townsend PA, Anhalt-Depies C, Locke C, Stenglein JL, Frett S, Martin KJ, Singh A, Van Deelen TR, Zuckerberg B. 2019. Making inference with messy (citizen science) data: when are data accurate enough and how can they be improved? *Ecological Applications* 29:e01849 DOI 10.1002/EAP.1849.

- Costello MJ. 2009.** Motivating online publication of data. *BioScience* 59:418–427 DOI 10.1525/bio.2009.59.5.9.
- Costello MJ, Michener WK, Gahegan M, Zhang ZQ, Bourne PE. 2013.** Biodiversity data should be published, cited, and peer reviewed. *Trends in Ecology and Evolution* 28:454–461 DOI 10.1016/j.tree.2013.05.002.
- Costello MJ, Wieczorek J. 2014.** Best practice for biodiversity data management and publication. *Biological Conservation* 173:68–73 DOI 10.1016/J.BIOCON.2013.10.018.
- Crandall KA, Buhay JE. 2007.** Global diversity of crayfish (Astacidae, Cambaridae, and Parastacidae—Decapoda) in freshwater. In: Balian EV, Lévêque C, Segers H, Martens K, eds. *Freshwater animal diversity assessment. Developments in hydrobiology, vol 198.* Dordrecht: Springer, 295–301 DOI 10.1007/978-1-4020-8259-7_32.
- Crandall KA, De Grave S. 2017.** An updated classification of the freshwater crayfishes (Decapoda: Astacidea) of the world, with a complete species list. *Journal of Crustacean Biology* 37:615–653 DOI 10.1093/jcbiol/rux070.
- Domisch S, Amatulli G, Jetz W. 2015.** Near-global freshwater-specific environmental variables for biodiversity analyses in 1 km resolution. *Scientific Data* 2:150073 DOI 10.1038/sdata.2015.73.
- Ejsmont-Karabin J. 2019.** Does the world need faunists? Based on rotifer (Rotifera) occurrence reflections on the role of faunistic research in ecology. *International Review of Hydrobiology* 104:49–56 DOI 10.1002/IROH.201901991.
- Emery-Butcher HE, Beatty SJ, Robson BJ. 2020.** The impacts of invasive ecosystem engineers in freshwaters: A review. *Freshwater Biology* 65:999–1015 DOI 10.1111/FWB.13479.
- Fetzner JW, Crandall KA. 2003.** Linear habitats and the nested clade analysis: an empirical evaluation of geographic versus river distances using an ozark crayfish (Decapoda: Cambaridae). *Evolution* 57:2101–2118 DOI 10.1111/J.0014-3820.2003.TB00388.X.
- Fišer C. 2019.** Collaborative databasing should be encouraged. *Trends in Ecology and Evolution* 34:184–185 DOI 10.1016/j.tree.2018.12.001.
- Führding-Potschkat P, Kreft H, Ickert-Bond SM. 2022.** Influence of different data cleaning solutions of point-occurrence records on downstream macroecological diversity models. *Ecology and Evolution* 12:e9168 DOI 10.1002/ECE3.9168.
- Gonzalez A, Vihervaara P, Balvanera P, Bates AE, Bayraktarov E, Bellingham PJ, Bruder A, Campbell J, Catchen MD, Cavender-Bares J, Chase J, Coops N, Costello MJ, Czúcz B, Delavaud A, Dornelas M, Dubois G, Duffy EJ, Eggermont H, Fernandez M, Fernandez N, Ferrier S, Geller GN, Gill M, Gravel D, Guerra CA, Guralnick R, Harfoot M, Hirsch T, Hoban S, Hughes AC, Hugo W, Hunter ME, Isbell F, Jetz W, Juergens N, Kissling WD, Krug CB, Kullberg P, Le Bras Y, Leung B, Londoño Murcia MC, Lord JM, Loreau M, Luers A, Ma K, MacDonald AJ, Maes J, McGeoch M, Mihoub JB, Millette KL, Molnar Z, Montes E, Mori AS, Muller-Karger FE, Muraoka H, Nakaoka M, Navarro L, Newbold T, Niamir A, Obura D, O’Connor M, Paganini M, Pelletier D, Pereira H, Poisot T, Pollock LJ, Purvis A, Radulovici A, Rocchini D, Roeoesli C, Schaepman M, Schaepman-Strub G, Schmeller DS,**

- Schmiedel U, Schneider FD, Shakya MM, Skidmore A, Skowno AL, Takeuchi Y, Tuanmu MN, Turak E, Turner W, Urban MC, Urbina-Cardona N, Valbuena R, Van de Putte A, Van Havre B, Wingate VR, Wright E, Torrelío CZ. 2023. A global biodiversity observing system to unite monitoring and guide action. *Nature Ecology & Evolution* 7(12):1947–1952 DOI 10.1038/s41559-023-02171-0.
- Graham CH, Elith J, Hijmans RJ, Guisan A, Townsend Peterson A, Loiselle BA, Anderson RP, Dudk M, Ferrier S, Huettmann F, Leathwick J, Lehmann A, Li J, Lohmann L, Loiselle B, Manion G, Moritz C, Nakamura M, Nakazawa Y, Overton J, Phillips S, Richardson K, Pereira RS, Schapire R, Soberón J, Williams S, Wisz M, Zimmermann N. 2008. The influence of spatial errors in species occurrence data used in distribution models. *Journal of Applied Ecology* 45:239–247 DOI 10.1111/J.1365-2664.2007.01408.X.
- Grandjean F, Gilbert C, Razafimafondy F, Vucić M, Delaunay C, Gindre P, Bouchard J, Raimond M, Moumen B. 2019. A new bunya-like virus associated with mass mortality of white-clawed crayfish in the wild. *Virology* 533:115–124 DOI 10.1016/J.VIROL.2019.05.014.
- Guareschi S, Cancellario T, Oficialdegui FJ, Clavero M. 2024. Insights from the past: Invasion trajectory and niche trends of a global freshwater invader. *Global Change Biology* 30:e17059 DOI 10.1111/GCB.17059.
- Guiaşu RC, Labib M. 2021. The unreliable concept of native range as applied to the distribution of the rusty crayfish (*Faxonius rusticus*) in North America. *Hydrobiologia* 848:1177–1205 DOI 10.1007/s10750-021-04523-y.
- Guiaşu RC, Barr DW, Dunham DW. 1996. Distribution and status of crayfishes of the genera *cambarus* and *fallicambarus* (Decapoda: Cambaridae) in Ontario, Canada. *Journal of Crustacean Biology* 16:373–383 DOI 10.1163/193724096X00162.
- Guisan A, Zimmermann NE. 2000. Predictive habitat distribution models in ecology. *Ecological Modelling* 135:147–186 DOI 10.1016/S0304-3800(00)00354-9.
- Guralnick RP, Wiczeorek J, Beaman R, Hijmans RJ. 2006. BioGeomancer: Automated georeferencing to map the world's biodiversity data. *PLOS Biology* 4:e381 DOI 10.1371/JOURNAL.PBIO.0040381.
- Hannah K, Haddaway NR, Fuller RA, Amano T. 2024. Language inclusion in ecological systematic reviews and maps: Barriers and perspectives. *Research Synthesis Methods* 15:466–482 DOI 10.1002/JRSM.1699.
- Ion MC, Ács A-R, Laza AV, Lorincz I, Livadariu D, Lamoly AM, Goia B, Togor A, Iorgu EI, Ştefan A, Popa OP, Pârvulescu L. 2024. Conservation status of the idle crayfish *Austropotamobius bihariensis* Pârvulescu, 2019. *Global Ecology and Conservation* 50:e02847 DOI 10.1016/J.GECCO.2024.E02847.
- Jetz W, McGeoch MA, Guralnick R, Ferrier S, Beck J, Costello MJ, Fernandez M, Geller GN, Keil P, Merow C, Meyer C, Muller-Karger FE, Pereira HM, Regan EC, Schmeller DS, Turak E. 2019. Essential biodiversity variables for mapping and monitoring species populations. *Nature Ecology & Evolution* 3(4):539–551 DOI 10.1038/s41559-019-0826-1.

- Jiménez-Valverde A, Lobo JM, Hortal J. 2008.** Not as good as they seem: the importance of concepts in species distribution modelling. *Diversity and Distributions* **14**:885–890 DOI [10.1111/J.1472-4642.2008.00496.X](https://doi.org/10.1111/J.1472-4642.2008.00496.X).
- Jussila J, Edsman L. 2020.** Relaxed attitude towards spreading of alien crayfish species affects protection of native crayfish species: case studies and lessons learnt from a Fennoscandian viewpoint. *Freshwater Crayfish* **25**:39–46 DOI [10.5869/FC.2020.V25-1.039](https://doi.org/10.5869/FC.2020.V25-1.039).
- Jussila J, Edsman L, Maguire I, Diéguez-Uribeondo J, Theissinger K. 2021.** Money kills native ecosystems: European crayfish as an example. *Frontiers in Ecology and Evolution* **9**:648495 DOI [10.3389/FEVO.2021.648495](https://doi.org/10.3389/FEVO.2021.648495).
- Kaufman D, McKay N, Routson C, Erb M, Davis B, Heiri O, Jaccard S, Tierney J, Dätwyler C, Axford Y, Brussel T, Cartapanis O, Chase B, Dawson A, De Vernal A, Engels S, Jonkers L, Marsicek J, Moffa-Sánchez P, Morrill C, Orsi A, Rehfeld K, Saunders K, Sommer PS, Thomas E, Tonello M, Tóth M, Vachula R, Andreev A, Bertrand S, Biskaborn B, Bringué M, Brooks S, Caniupán M, Chevalier M, Cwynar L, Emile-Geay J, Fegyveresi J, Feurdean A, Finsinger W, Fortin MC, Foster L, Fox M, Gajewski K, Grosjean M, Hausmann S, Heinrichs M, Holmes N, Ilyashuk B, Ilyashuk E, Juggins S, Khider D, Koinig K, Langdon P, Larocque-Tobler I, Li J, Lotter A, Luoto T, Mackay A, Magyari E, Malevich S, Mark B, Massaferrero J, Montade V, Nazarova L, Novenko E, Pařil P, Pearson E, Peros M, Pienitz R, Plóciennik M, Porinchu D, Potito A, Rees A, Reinemann S, Roberts S, Rolland N, Salonen S, Self A, Seppä H, Shala S, St-Jacques JM, Stenni B, Syrykh L, Tarrats P, Taylor K, Van den Bos V, Velle G, Wahl E, Walker I, Wilmshurst J, Zhang E, Zhilich S. 2020.** A global database of Holocene paleotemperature records. *Scientific Data* **7**(1):115 DOI [10.1038/s41597-020-0445-3](https://doi.org/10.1038/s41597-020-0445-3).
- Kopperud BT, Lidgard S, Liow LH. 2022.** Enhancing georeferenced biodiversity inventories: automated information extraction from literature records reveal the gaps. *PeerJ* **10**:e13921 DOI [10.7717/peerj.13921](https://doi.org/10.7717/peerj.13921).
- Kosmala M, Wiggins A, Swanson A, Simmons B. 2016.** Assessing data quality in citizen science. *Frontiers in Ecology and the Environment* **14**:551–560 DOI [10.1002/FEE.1436](https://doi.org/10.1002/FEE.1436).
- Kouba A, Petrusek A, Kozák P. 2014.** Continental-wide distribution of crayfish species in Europe: update and maps. *Knowledge and Management of Aquatic Ecosystems* **413**:05 DOI [10.1051/kmae/2014007](https://doi.org/10.1051/kmae/2014007).
- Li Y, Bearup D, Liao J. 2020.** Habitat loss alters effects of intransitive higher-order competition on biodiversity: a new metapopulation framework. *Proceedings of the Royal Society B: Biological Sciences* **287**:20201571 DOI [10.1098/rspb.2020.1571](https://doi.org/10.1098/rspb.2020.1571).
- Liang J, Gamarra JGP. 2020.** The importance of sharing global forest data in a world of crises. *Scientific Data* **7**:424 DOI [10.1038/s41597-020-00766-x](https://doi.org/10.1038/s41597-020-00766-x).
- Lidova J, Buric M, Kouba A, Velisek J. 2019.** Acute toxicity of two pyrethroid insecticides for five non-indigenous crayfish species in Europe. *Veterinarni Medicina* **64**:125–133 DOI [10.17221/136/2018-VETMED](https://doi.org/10.17221/136/2018-VETMED).

- Lipták B, Kouba A, Patoka J, Paunović M, Prokop P. 2024.** Biological invasions and invasive species in freshwaters: perception of the general public. *Human Dimensions of Wildlife* **29**:48–63 DOI [10.1080/10871209.2023.2177779](https://doi.org/10.1080/10871209.2023.2177779).
- Lipták B, Prati S, Oficialdegui FJ, Apfelová M, Pekárová S, Kautman J, Janský V, Kouba A. 2024.** First populations of invasive red swamp crayfish flourish in Slovakia. *BioInvasions Records* **13**:825–841 DOI [10.3391/bir.2024.13.3.20](https://doi.org/10.3391/bir.2024.13.3.20).
- Liu C, Wolter C, Xian W, Jeschke JM. 2020.** Species distribution models have limited spatial transferability for invasive species. *Ecology Letters* **23**:1682–1692 DOI [10.1111/ele.13577](https://doi.org/10.1111/ele.13577).
- Lodge DM, Deines A, Gherardi F, Yeo DCJ, Arcella T, Baldrige AK, Barnes MA, Lindsay Chadderton W, Feder JL, Gantz CA, Howard GW, Jerde CL, Peters BW, Peters JA, Sargent LW, Turner CR, Wittmann ME, Zeng Y. 2012.** Global introductions of crayfishes: Evaluating the impact of species invasions on ecosystem services. *Annual Review of Ecology, Evolution, and Systematics* **43**:449–472 DOI [10.1146/annurev-ecolsys-111511-103919](https://doi.org/10.1146/annurev-ecolsys-111511-103919).
- Longshaw M. 2011.** Diseases of crayfish: A review. *Journal of Invertebrate Pathology* **106**:54–70 DOI [10.1016/J.JIP.2010.09.013](https://doi.org/10.1016/J.JIP.2010.09.013).
- Manfrin C, Souty-Grosset C, Anastácio PM, Reynolds J, Giulianini PG. 2019.** Detection and control of invasive freshwater crayfish: From traditional to innovative methods. *Diversity* **5**(11):5 DOI [10.3390/D11010005](https://doi.org/10.3390/D11010005).
- Marques V, Milhau T, Albouy C, Dejean T, Manel S, Mouillot D, Juhel J. 2021.** GAPeDNA: assessing and mapping global species gaps in genetic databases for eDNA metabarcoding. *Diversity and Distributions* **27**:1880–1892 DOI [10.1111/ddi.13142](https://doi.org/10.1111/ddi.13142).
- Martínez-Ríos M, Martín-Torrijos L, Diéguez-Uribeondo J. 2023.** Protocols for studying the crayfish plague pathogen, *Aphanomyces astaci*, and its host-pathogen interactions. *Journal of Invertebrate Pathology* **201**:108018 DOI [10.1016/J.JIP.2023.108018](https://doi.org/10.1016/J.JIP.2023.108018).
- McClenachan L, Ferretti F, Baum JK. 2012.** From archives to conservation: why historical data are needed to set baselines for marine animals and ecosystems. *Conservation Letters* **5**:349–359 DOI [10.1111/j.1755-263X.2012.00253.x](https://doi.org/10.1111/j.1755-263X.2012.00253.x).
- Meier R, Dikow T. 2004.** Significance of specimen databases from taxonomic revisions for estimating and mapping the global species diversity of invertebrates and repatriating reliable specimen data. *Conservation Biology* **18**:478–488 DOI [10.1111/J.1523-1739.2004.00233.X](https://doi.org/10.1111/J.1523-1739.2004.00233.X).
- Meyer C, Weigelt P, Kreft H. 2016.** Multidimensional biases, gaps and uncertainties in global plant occurrence information. *Ecology Letters* **19**:992–1006 DOI [10.1111/ELE.12624](https://doi.org/10.1111/ELE.12624).
- Miller AD, Inamine H, Buckling A, Roxburgh SH, Shea K. 2021.** How disturbance history alters invasion success: biotic legacies and regime change. *Ecology Letters* **24**:ele.13685 DOI [10.1111/ele.13685](https://doi.org/10.1111/ele.13685).
- Momot WT. 1995.** Redefining the role of crayfish in aquatic ecosystems. *Reviews in Fisheries Science* **3**:33–63 DOI [10.1080/10641269509388566](https://doi.org/10.1080/10641269509388566).
- Neculae A, Barnett ZC, Miok K, Dalosto MM, Kuklina I, Kawai T, Santos S, Furse JM, Sîrbu OI, Stoeckel JA, Pârvolescu L. 2024.** Living on the edge: Crayfish as drivers

- to anoxification of their own shelter microenvironment. *PLOS ONE* **19**:e0287888 DOI [10.1371/JOURNAL.PONE.0287888](https://doi.org/10.1371/JOURNAL.PONE.0287888).
- Oficialdegui FJ, Sánchez MI, Clavero M. 2020. One century away from home: how the red swamp crayfish took over the world. *Reviews in Fish Biology and Fisheries* **30**:121–135 DOI [10.1007/s11160-020-09594-z](https://doi.org/10.1007/s11160-020-09594-z).
- Pârvulescu L, Iorgu E-I, Zaharia C, Ion MC, Satmari A, Krapal A-M, Popa O-P, Miok K, Petrescu I, Popa L-O. 2020. The future of endangered crayfish in light of protected areas and habitat fragmentation. *Scientific Reports* **10**(1):14870 DOI [10.1038/s41598-020-71915-w](https://doi.org/10.1038/s41598-020-71915-w).
- Pârvulescu L, Zaharia C, Groza M-I, Csillik O, Satmari A, Drăguț L. 2016. Flash-flood potential: a proxy for crayfish habitat stability. *Ecohydrology* **9**:1507–1516 DOI [10.1002/eco.1744](https://doi.org/10.1002/eco.1744).
- Pereyra PJ, Guiãșu RC. 2020. Debate over the importance and meaning of native range in invasion biology: reply to Courchamp et al. *Conservation Biology* **34**:1044–1046 DOI [10.1111/COBI.13529](https://doi.org/10.1111/COBI.13529).
- Pyšek P, Hulme PE, Simberloff D, Bacher S, Blackburn TM, Carlton JT, Dawson W, Essl F, Foxcroft LC, Genovesi P, Jeschke JM, Kühn I, Liebhold AM, Mandrak NE, Meyerson LA, Pauchard A, Pergl J, Roy HE, Seebens H, Van Kleunen M, Vilà M, Wingfield MJ, Richardson DM. 2020. Scientists' warning on invasive alien species. *Biological Reviews* **95**:1511–1534 DOI [10.1111/brv.12627](https://doi.org/10.1111/brv.12627).
- R Core Team. 2024. R: a language and environment for statistical computing. Vienna: R Foundation for Statistical Computing. Available at <https://www.r-project.org>.
- Reaser JK, Burgiel SW, Kirkey J, Brantley KA, Veatch SD, Burgos-Rodríguez J. 2019. The early detection of and rapid response (EDRR) to invasive species: a conceptual framework and federal capacities assessment. *Biological Invasions* **22**:1–19 DOI [10.1007/s10530-019-02156-w](https://doi.org/10.1007/s10530-019-02156-w).
- Reaser JK, Frey M, Meyers NM. 2019. Invasive species watch lists: guidance for development, communication, and application. *Biological Invasions* **22**:47–51 DOI [10.1007/s10530-019-02176-6](https://doi.org/10.1007/s10530-019-02176-6).
- Reichman OJ, Jones MB, Schildhauer MP. 2011. Challenges and opportunities of open data in ecology. *Science* **331**:703–705 DOI [10.1126/SCIENCE.1197962](https://doi.org/10.1126/SCIENCE.1197962).
- Richman NI, Böhm M, Adams SB, Alvarez F, Bergery EA, Bunn JJS, Burnham Q, Cordeiro J, Coughran J, Crandall KA, Dawkins KL, Di Stefano RJ, Doran NE, Edsman L, Eversole AG, Füreder L, Furse JM, Gherardi F, Hamr P, Holdich DM, Horwitz P, Johnston K, Jones CM, Jones JPG, Jones RL, Jones TG, Kawai T, Lawler S, López-Mejía M, Miller RM, Pedraza-Lara C, Reynolds JD, Richardson AMM, Schultz MB, Schuster GA, Sibley PJ, Souty-Grosset C, Taylor CA, Thoma RF, Walls J, Walsh TS, Collen B. 2015. Multiple drivers of decline in the global status of freshwater crayfish (Decapoda: Astacidea). *Philosophical Transactions of the Royal Society B: Biological Sciences* **370**:20140060 DOI [10.1098/rstb.2014.0060](https://doi.org/10.1098/rstb.2014.0060).
- Robinson OJ, Ruiz-Gutierrez V, Reynolds MD, Golet GH, Strimas-Mackey M, Fink D. 2020. Integrating citizen science data with expert surveys increases accuracy and

- spatial extent of species distribution models. *Diversity and Distributions* 26:976–986 DOI 10.1111/DDI.13068.
- Rocchini D, Hortal J, Lengyel S, Lobo JM, Jiménez-Valverde A, Ricotta C, Bacaro G, Chiarucci A. 2011.** Accounting for uncertainty when mapping species distributions: The need for maps of ignorance. *Progress in Physical Geography* 35:211–226 DOI 10.1177/0309133311399491.
- Rodríguez JP, Keith DA, Rodríguez-Clark KM, Murray NJ, Nicholson E, Regan TJ, Miller RM, Barrow EG, Bland LM, Boe K, Brooks TM, Oliveira-Miranda MA, Spalding M, Wit P. 2015.** A practical guide to the application of the IUCN Red List of Ecosystems criteria. *Philosophical Transactions of the Royal Society B: Biological Sciences* 370:20140003 DOI 10.1098/rstb.2014.0003.
- Salomaki ED, Eme L, Brown MW, Kolisko M. 2020.** Releasing uncurated datasets is essential for reproducible phylogenomics. *Nature Ecology & Evolution* 4:1435–1437 DOI 10.1038/s41559-020-01296-w.
- Șandric I, Satmari A, Zaharia C, Petrovici M, Cîmpean M, Battes K-P, David D-C, Pacioglu O, Weiperth A, Gál B, Pîrvu M, Muntean H, Neagul M, Spătaru A, Toma CG, Pârvulescu L. 2019.** Integrating catchment land cover data to remotely assess freshwater quality: a step forward in heterogeneity analysis of river networks. *Aquatic Sciences* 81:26 DOI 10.1007/s00027-019-0624-5.
- Satmari A, Miok K, Ion MC, Zaharia C, Schrimpf A, Pârvulescu L. 2023.** Headwater refuges: flow protects *Austropotamobius* crayfish from *Faxonius limosus* invasion. *NeoBiota* 89:71–94 DOI 10.3897/neobiota.89.110085.
- Sax DF, Gaines SD. 2003.** Species diversity: from global decreases to local increases. *Trends in Ecology and Evolution* 18:561–566 DOI 10.1016/S0169-5347(03)00224-6.
- Scholtz G, Richter S. 1995.** Phylogenetic systematics of the reptantian Decapoda (Crustacea, Malacostraca). *Zoological Journal of the Linnean Society* 113:289–328 DOI 10.1006/ZJLS.1995.0011.
- Shen C, Appling AP, Gentine P, Bandai T, Gupta H, Tartakovsky A, Baity-Jesi M, Fenicia F, Kifer D, Li L, Liu X, Ren W, Zheng Y, Harman CJ, Clark M, Farthing M, Feng D, Kumar P, Aboelyazeed D, Rahmani F, Song Y, Beck HE, Bindas T, Dwivedi D, Fang K, Höge M, Rackauckas C, Mohanty B, Roy T, Xu C, Lawson K. 2023.** Differentiable modelling to unify machine learning and physical models for geosciences. *Nature Reviews Earth & Environment* 4(8):552–567 DOI 10.1038/s43017-023-00450-9.
- Soto I, Ahmed DA, Beidas A, Oficialdegui FJ, Tricarico E, Angeler DG, Amatulli G, Briski E, Datry T, Dohet A, Domisch S, England J, Feio MJ, Forcellini M, Johnson RK, Jones JI, Larrañaga A, L’Hoste L, Murphy JF, Schäfer RB, Shen LQ, Kouba A, Haubrock PJ. 2023.** Long-term trends in crayfish invasions across European rivers. *Science of the Total Environment* 867:161537 DOI 10.1016/J.SCITOTENV.2023.161537.
- Soto I, Balzani P, Carneiro L, Cuthbert RN, Macêdo R, Tarkan AS, Ahmed DA, Bang A, Bacela-Spychalska K, Bailey SA, Baudry T, Ballesteros-Mejia L, Bortolus A, Briski E, Britton JR, Buřič M, Camacho-Cervantes M, Cano-Barbacil C, Copilaș-Ciocianu**

- D, Coughlan NE, Courtois P, Csabai Z, Dalu T, De Santis V, Dickey JWE, Dimarco RD, Falk-Andersson J, Fernandez RD, Florencio M, Franco ACS, García-Berthou E, Giannetto D, Glavendekic MM, Grabowski M, Heringer G, Herrera I, Huang W, Kamelamela KL, Kirichenko NI, Kouba A, Kourantidou M, Kurtul I, Laufer G, Lipták B, Liu C, López-López E, Lozano V, Mammola S, Marchini A, Meshkova V, Milardi M, Musolin DL, Nuñez MA, Oficialdegui FJ, Patoka J, Pattison Z, Pincheira-Donoso D, Piria M, Probert AF, Rasmussen JJ, Renault D, Ribeiro F, Rilov G, Robinson TB, Sanchez AE, Schwindt E, South J, Stoett P, Verreycken H, Vilizzi L, Wang Y-J, Watari Y, Wehi PM, Weiperth A, Wiberg-Larsen P, Yapıcı S, Yoğurtçuoğlu B, Zenni RD, Galil BS, Dick JTA, Russell JC, Ricciardi A, Simberloff D, Bradshaw CJA, Haubrock PJ. 2024. Taming the terminological tempest in invasion science. *Biological Reviews* **99**:1357–1390 DOI [10.1111/BRV.13071](https://doi.org/10.1111/BRV.13071).
- Strand DA, Jinnerot T, Aspán A, Viljamaa-Dirks S, Heinikainen S, Rolén E, Vrålstad T. 2023. Molecular detection of *Aphanomyces astaci* –an improved species specific qPCR assay. *Journal of Invertebrate Pathology* **201**:108008 DOI [10.1016/J.JIP.2023.108008](https://doi.org/10.1016/J.JIP.2023.108008).
- Strand DA, Johnsen SI, Rusch JC, Agersnap S, Larsen WB, Knudsen SW, Møller PR, Vrålstad T. 2019. Monitoring a Norwegian freshwater crayfish tragedy: eDNA/snapshots of invasion, infection and extinction. *Journal of Applied Ecology* **56**:1661–1673 DOI [10.1111/1365-2664.13404](https://doi.org/10.1111/1365-2664.13404).
- Stratton CE, Kabalan BA, Bolds SA, Reisinger LS, Behringer DC, Bojko J. 2023. *Cambaraspora faxoni* n. sp. (Microsporidia: Glugeida) from native and invasive crayfish in the USA and a novel host of *Cambaraspora floridanus*. *Journal of Invertebrate Pathology* **199**:107949 DOI [10.1016/J.JIP.2023.107949](https://doi.org/10.1016/J.JIP.2023.107949).
- Taylor CA, Di Stefano RJ, Larson ER, Stoeckel J. 2019. Towards a cohesive strategy for the conservation of the United States' diverse and highly endemic crayfish fauna. *Hydrobiologia* **846**(1):39–58 DOI [10.1007/S10750-019-04066-3](https://doi.org/10.1007/S10750-019-04066-3).
- Thessen AE, Cui H, Mozzherin D. 2012. Applications of natural language processing in biodiversity science. *Advances in Bioinformatics* **2012**:391574 DOI [10.1155/2012/391574](https://doi.org/10.1155/2012/391574).
- Troudet J, Grandcolas P, Blin A, Vignes-Lebbe R, Legendre F. 2017. Taxonomic bias in biodiversity data and societal preferences. *Scientific Reports* **7**(1):9132 DOI [10.1038/s41598-017-09084-6](https://doi.org/10.1038/s41598-017-09084-6).
- Ungureanu E, Mojžišová M, Tangerman M, Ion MC, Parvulescu L, Petrussek A. 2020. The spatial distribution of *Aphanomyces astaci* genotypes across Europe: introducing the first data from Ukraine. *Freshwater Crayfish* **25**:77–87 DOI [10.5869/fc.2020.v25-1.077](https://doi.org/10.5869/fc.2020.v25-1.077).
- Valdecasas AG, Camacho AI. 2003. Conservation to the rescue of taxonomy. *Biodiversity and Conservation* **12**:1113–1117 DOI [10.1023/A:1023082606162](https://doi.org/10.1023/A:1023082606162).
- Villero D, Pla M, Camps D, Ruiz-Olmo J, Brotons L. 2017. Integrating species distribution modelling into decision-making to inform conservation actions. *Biodiversity and Conservation* **26**:251–271 DOI [10.1007/s10531-016-1243-2](https://doi.org/10.1007/s10531-016-1243-2).

- Wieczorek J, Guo Q, Hijmans RJ. 2004.** The point-radius method for georeferencing locality descriptions and calculating associated uncertainty. *International Journal of Geographical Information Science* **18**:745–767 DOI [10.1080/13658810412331280211](https://doi.org/10.1080/13658810412331280211).
- Wilkinson MD, Dumontier M, Aalbersberg IJJ, Appleton G, Axton M, Baak A, Blomberg N, Boiten JW, Da Silva Santos LB, Bourne PE, Bouwman J, Brookes AJ, Clark T, Crosas M, Dillo I, Dumon O, Edmunds S, Evelo CT, Finkers R, Gonzalez-Beltran A, Gray AJG, Groth P, Goble C, Grethe JS, Heringa J, Ct Hoen PA, Hooft R, Kuhn T, Kok R, Kok J, Lusher SJ, Martone ME, Mons A, Packer AL, Persson B, Rocca-Serra P, Roos M, Van Schaik R, Sansone SA, Schultes E, Sengstag T, Slater T, Strawn G, Swertz MA, Thompson M, Van Der Lei J, Van Mulligen E, Velterop J, Waagmeester A, Wittenburg P, Wolstencroft K, Zhao J, Mons B. 2016.** The FAIR guiding principles for scientific data management and stewardship. *Scientific Data* **3**(1):160018 DOI [10.1038/sdata.2016.18](https://doi.org/10.1038/sdata.2016.18).
- World Intellectual Property Organization. 2022.** Nice agreement concerning the international classification of goods and services for the purposes of the registration of marks. 11th edn. Available at <https://www.wipo.int/treaties/en/classification/nice/>.
- Zingre T, Pisano SRR, Wildi N, Dawson KLD, Cristina E, Seuberlich T, Schmidt-Posthaus H. 2023.** Detection of novel RNA viruses in wild noble crayfish (*Astacus astacus*): A virome analysis in Swiss water bodies. *Journal of Invertebrate Pathology* **201**:108011 DOI [10.1016/J.JIP.2023.108011](https://doi.org/10.1016/J.JIP.2023.108011).