Camtrap DP: An open standard for the FAIR exchange and archiving of camera trap data

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Abstract

Camera trapping has revolutionized wildlife ecology and conservation by providing automated data acquisition, leading to the accumulation of massive amounts of camera trap data worldwide. Although management and processing of camera trap-derived Big Data are becoming increasingly solvable with the help of scalable cyber-infrastructures, harmonization and exchange of the data remain limited, hindering its full potential. We present a new data exchange format, the Camera Trap Data Package (Camtrap DP), designed to allow users to easily exchange, harmonize and archive camera trap data at local to global scales. Camtrap DP structures camera trap data in a simple yet flexible data model consisting of three tables (Deployments, Media, and Observations) that supports a wide range of camera deployment designs, classification techniques (e.g., human and AI, media-based and event-based) and analytical use cases, from compiling species occurrence data through distribution, occupancy and activity modeling to density estimation. The format further achieves interoperability by building upon existing standards, Frictionless Data Package in particular, which is supported by a suite of open software tools to read and validate data. Camtrap DP is the consensus of a long, in-depth, consultation and outreach process with standard and software developers, the main existing camera trap data management platforms, major players in the field of camera trapping, and the Global Biodiversity Information Facility (GBIF). Under the umbrella of the Biodiversity Information Standards (TDWG), Camtrap DP has been developed openly, collaboratively, and with version control from the start and we encourage camera trapping users and developers to join the discussion and contribute to the further development and adoption of this standard.

Introduction

Populations of many species across the globe are undergoing dramatic alterations in their abundance and distribution, due to a combination of climate-driven and anthropogenic impacts that can either favor or negatively affect species persistence in certain ecosystems (Dornelas *et al.*, 2019). On the one hand, many species are rapidly declining due to anthropogenic stressors acting at different spatio-temporal scales (Dirzo *et al.*, 2014; Venter *et al.*, 2016; Ripple *et al.*, 2017; Bar-On, Phillips & Milo, 2018). Terrestrial large mammals are at high risk of extinction and this has caused widespread trophic downgrading, i.e., the removal of apex predators and primary consumers (i.e. large carnivores and herbivores) from a majority of Earth's ecosystems (Estes *et al.*, 2011). Indeed, as much as 60% of large herbivore species worldwide are threatened with extinction (Ripple *et al.*, 2015). As a consequence, a great loss of food web links has been recorded (Fricke *et al.*, 2022), putting important ecological interactions and functions at risk (Dirzo *et al.*, 2014; IPBES, 2018). For example, the impact of defaunation on tropical forests (i.e. the "empty forest" syndrome; Redford, 1992) has compromised key functional relations such as seed consumption, herbivory, pollination, and seed dispersal (Benítez-López *et al.*, 2019; Bogoni *et al.*, 2023).

On the other hand, extensive areas are experiencing strong increases in some wildlife populations due to land use change such as forest recovery after land abandonment, but also increasing food availability due to forestry and agricultural practices (Perpiña *et al.*, 2018) and successful conservation policies (e.g., US Endangered Species Act 1973; Habitat Directive EU Commission 1997). As a result, several medium-to-large sized herbivores and carnivores have increased in number and distribution range (from beaver *Castor fiber* to red deer *Cervus elaphus* and white-tailed deer *Odocoileus virgianus* to wild boar *Sus scrofa*, otter *Lutra lutra* and wolves *Canis lupus;* Chapron *et al.*, 2014; Cimatti *et al.*, 2021). Typically, populations of functionally generalist and ecologically plastic species have increased in human modified landscapes, leading to a re-establishment of more complex ecosystems on the one hand, but also to an increase in the likelihood of conflicts, such as crop damage, depredation on livestock, browsing impact on natural tree regeneration, damage to tree plantations, and disease transmission and traffic accidents at the human-wildlife interface (Côté *et al.*, 2004; Rodríguez-Morales, Díaz-Varela & Marey-Pérez, 2013; Apollonio *et al.*, 2017; Martin *et al.*, 2018; Gibb *et al.*, 2020).

These opposing trends, where wildlife populations are either strongly declining or increasing, highlight that the conservation of wildlife and the mitigation of human-wildlife conflicts are strongly intertwined. To understand and manage these relations at different spatio-temporal scales requires big data obtained through extensive networks and standardized monitoring protocols (Sutherland *et al.*, 2004; Buxton *et al.*, 2021).

One well-established method for monitoring wildlife, and especially medium-to-large mammals, is camera trapping, a non-invasive tool to collect field data on animal abundance, distribution, behavior and temporal activity across varying spatial scales (Burton *et al.*, 2015; Rovero & Zimmermann, 2016; Wearn & Glover-Kapfer, 2019; Delisle *et al.*, 2021). Camera traps are autonomous devices that, either automatically triggered by the passage of animals or as time-lapse (see Welbourne *et al.*, 2016), capture images or videos of a wide range of animals and are particularly effective in collecting rich data simultaneously for many species. In addition, they can capture 'by-catch data' on non-target species, species traits or background environmental conditions (Scotson *et al.*, 2017; Hofmeester *et al.*, 2019), making the collected data useful beyond the scope of the focal species monitoring. Camera traps are used by both professional and citizen scientists with the unique property of producing records of multiple species occurrences that are verifiable as opposed to direct visual observations.

The automated data acquisition provided by camera trapping has moved wildlife ecology and conservation into the Big-Data era (Michener & Jones, 2012; Hampton *et al.*, 2013; Farley *et al.*, 2018). The massive accumulation of camera trap data worldwide (over 100 millions of confirmed digital animal observations; Steenweg *et al.*, 2016; Kays, McShea & Wikelski, 2020; Delisle *et al.*, 2021) potentially allows for large-scale interdisciplinary research and low-cost monitoring of wildlife. However, the exploitation of the full potential of camera trap-derived Big Data requires effective and scalable (i.e., from local landscapes to the entire planet) cyber-infrastructures and tools for collaborative data collection, management, processing, harmonization and exchange (Hampton *et al.*, 2013; González Talaván *et al.*, 2014; Steenweg *et al.*, 2016; Farley *et al.*, 2018; Sequeira *et al.*, 2021). Beyond the initial technical development, these tools need the establishment of a network of users and a direct involvement of the entire community to boost their implementation (Urbano, Cagnacci & Euromammals, 2021).

In recent years, the global camera trapping community has made significant progress towards building data management tools for camera trapping on a wide array of platforms (González Talaván *et al.*, 2014; Scotson *et al.*, 2017; Young, Rode-Margono & Amin, 2018) including desktop software (e.g., Wild.ID, Camelot, Camera Base; (Hendry & Mann, 2018; Tobler, 2022)), web applications (e.g., eMammal, Agouti, Wildlife Insights, TRAPPER; (Bubnicki, Churski &

Kuijper, 2016; Ahumada *et al.*, 2019; Casaer *et al.*, 2019; Kays *et al.*, 2020) and analytical packages (e.g., camtrapR, camtraptor; (Niedballa *et al.*, 2016; Oldoni & Desmet, 2022). Progress has also been made in the use of artificial intelligence (AI) to automate camera trap image processing. Computer vision can be used to efficiently filter out blank images (i.e., with no animal pictured on it), as well as humans (to be filtered out for privacy reasons) and identify animal species and individuals with high accuracy (Norouzzadeh *et al.*, 2018; Tabak *et al.*, 2018; Kellenberger, Tuia & Morris, 2020; Vidal *et al.*, 2021). If the pace of innovation continues in this field, most recorded material will be (semi-)automatically classified in the near future.

User communities have formed around centralized camera trap data repositories (e.g., Wildlife Insights, Agouti, Snapshot Safari, EuroCaM), which allow them to address big questions in wildlife conservation (Ahumada *et al.*, 2019; Kays *et al.*, 2020; Pardo *et al.*, 2021). These initiatives are important as they provide essential tools to many research groups, NGOs or individual researchers and conservationists to improve image acquisition, streamline image processing, facilitate data sharing, and guide and enhance data analysis (Ahumada *et al.*, 2019; Delisle *et al.*, 2021). Despite these important advances, arguably the largest portion of the global inventory of camera trap data remains isolated within individual data producers. Furthermore, the existing data management platforms and infrastructures remain relatively disconnected, with the risk of duplicated effort and missed opportunity for data integration. To connect existing data management platforms, we urgently need a common exchange format between the existing systems to maximize the potential of data sharing to address large-scale questions (Steenweg *et al.*, 2016; Rowcliffe, 2017; Farley *et al.*, 2018). In other words, there is a strong need to assure the FAIRness (Wilkinson *et al.*, 2016; Findable ("F"), Accessible ("A"), Interoperable ("I"), and Reusable ("R")) of the global circulation and harmonization of camera trap datasets in a format which is both machine- and human-readable.

However, despite its relevance for the community of ecologists and wildlife practitioners, there is presently no accepted and used standard for the exchange of camera trap data. The “Camera Trap Metadata Standard” (CTMS) published by Forrester *et al.* (2016) represents an important step towards this, but has failed to reach widespread adoption. In this paper, we describe a new data exchange format for camera trap data, the Camera Trap Data Package (Camtrap DP). It builds upon CTMS, aims to overcome its shortcomings and is designed to allow users to easily exchange, harmonize and archive camera trap data at local to global scales. Importantly, Camtrap DP is the consensus of a long, in-depth, consultation process among the main existing camera trap data management platforms as well as some of the major global players in the field of camera trapping (see author list).

Guiding principles

We developed Camtrap DP with two guiding principles: 1) it should allow easy and interoperable data exchange, and 2) it should be developed openly and collaboratively.

Interoperable data exchange was achieved in several ways. Camtrap DP structures camera trap data in a simple data model that supports a wide range of camera deployment designs (e.g., simple or systematic random, clustered, experimental, feature-targeted), classification techniques (e.g., human and AI, media-based and event-based) and analytical use cases (from compiling species occurrence data through distribution, occupancy and activity modeling to density estimation using different protocols like Random Encounter Model, spatial capture-recapture, or distance-sampling). Data can be exchanged among systems by transforming to and from this model. Where possible, we used terms from existing standards, such as Darwin Core (Wieczorek *et al.*, 2012), Audiovisual Core (Audiovisual Core Maintenance Group, 2023), Dublin Core, Data Cite Metadata Schema (DataCite Metadata Working Group, 2021) and vocabularies suggested by (Forrester *et al.*, 2016). We decided to adopt Frictionless Standards (https://specs.frictionlessdata.io), a collection of open specifications developed by the Frictionless Data project (Fowler, Barratt & Walsh, 2018) that offer a standardized way to describe datasets, data files and tabular data. Their main specification, Data Package (Walsh & Pollock, 2007), is a simple container format to package and describe a collection of files. Frictionless Standards are expressed as Javascript Object Notation (JSON) schemas—vocabularies that allow one to annotate and validate JSON documents—making them machine-readable and extensible. The machine-readability has led to the development of a suite of open-source software tools (e.g., Frictionless Framework; (Open Knowledge Foundation, 2022) in multiple programming languages to create and validate data: tools that are available for Camtrap DP users out-of-the-box. The inherent extensibility of JSON schemas allows communities to expand upon the generic Data Package requirements with domain-specific metadata and requirements. By using Frictionless Standards, Camtrap DP is both domain-specific and highly interoperable.

Camtrap DP has been developed openly, collaboratively, and with version control from the start. It was developed under Biodiversity Information Standards (TDWG) and has been licensed under the permissive MIT license (https://choosealicense.com/licenses/mit/), allowing anyone to use it. Suggestions for changes to the standard, including possible extensions, were, and continue to be, publicly discussed in an issue tracker (https://github.com/tdwg/camtrap-dp/issues) by a community of software developers and researchers, and are incorporated only after review and automated testing. Once a number of changes has been adopted, a new version of the standard is released using semantic versioning. This allows Camtrap DP to evolve over time, while making sure that software and datasets referring to older versions of the standard are still valid. The standard itself is maintained as JSON schemas, which are versioned using GitHub and presented as human-readable documentation at https://tdwg.github.io/camtrap-dp/.

Description of the standard

Following the Frictionless Data Package specification, a Camtrap DP dataset contains two types of files: a JSON descriptor file named `datapackage.json` with dataset-level **metadata** and tabular **data**, commonly expressed as CSV (comma-separated values) files. The descriptor file also includes the location and technical description of the data files (called 'Resources') and thus serves as an entry point to the dataset. Resources are described with the Data Resource specification (Walsh & Pollock, 2016), defining their name, path, encoding and CSV dialect, while the tabular data itself is described with Table Schema (Walsh & Pollock, 2012), defining field names, data types, constraints, missing values, primary keys and foreign keys.

The Camtrap DP standard (version 1.0-rc.1, see https://github.com/tdwg/camtrap-dp/releases/tag/1.0-rc.1 and Supplementary materials) extends the Data Package specification in two ways. First, it defines a Profile (`camtrap-dp-profile.json`) to capture the essential metadata of a camera trap study. This Profile makes a number of existing Data Package properties required (`contributors` and `created` date) and adds new ones (e.g., `project` information, `spatial`, `temporal`, and `taxonomic` scope). It purposely limits the scope of a dataset/package to a single study/project, which facilitates describing dataset-level properties. Secondly, it specifies the Resources to capture the data collected by the study. The fields and relationships of these Resources are described in three Table Schemas (`-table-schema.json`). For each property in the Profile and field in the Table Schemas, the data type and format are defined, whether it is required or optional, and whether values should be unique or follow a controlled vocabulary. The three resources collectively represent a data model to exchange camera trap data (Figure 1).

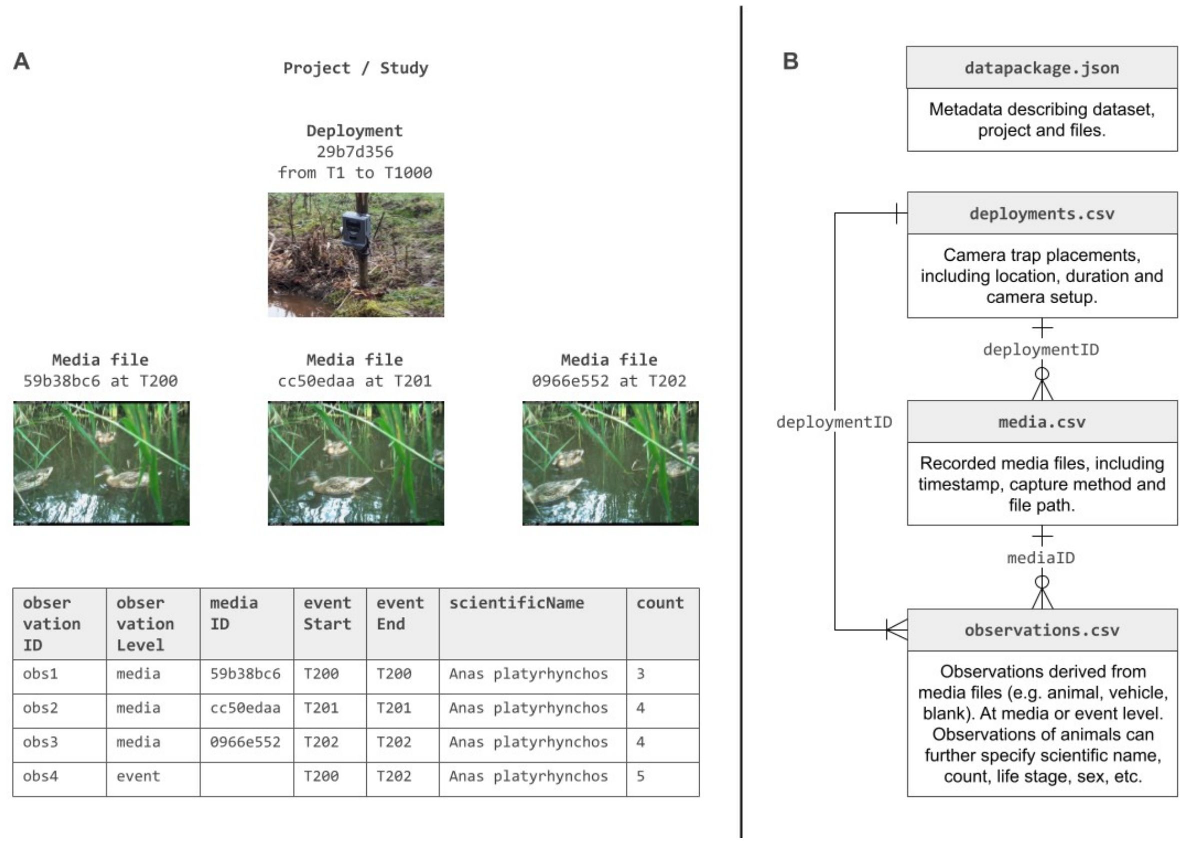

Figure 1: (A) Schematic representation of a camera trap project: camera traps are deployed at a location for a period (T1-T1000), recording media files (59b38bc6, cc50edaa, 0966e552). These can be classified into observations at media-level (obs1, obs2, obs3) or event-level (obs4). The total count of observed individuals for an event can be larger than what can be seen in a single media file. (B) Schema representing the structure of a Camtrap DP dataset: it contains one metadata file (datapackage.json) and three tabular data files (deployments.csv, media.csv, observations.csv). The relationships between the files are indicated with lines using entity relationship diagram notation.

Deployments is a table with information on the camera trap placements (deployments). It includes the location (`locationID`, `locationName`, `latitude`, `longitude`, `coordinateUncertainty`), duration (`deploymentStart`, `deploymentEnd`) and camera settings (e.g., `cameraModel`, `cameraDelay`, `cameraHeight`). It also allows to record bait use, feature type, habitat and comments, and to organize deployments in groups (`deploymentGroups`).

Media is a table with information on the media files (images/videos) recorded during deployments (`deploymentID`). It includes the recorded timestamp, capture method (motion detection or time lapse) and file information (e.g., `filePath`, `filePublic`, `fileMediatype`). No assumptions are made regarding the location of the media files themselves: they can be referenced with a local path or URL.

Observations is a table with information on the observations (also called classifications) derived from the media files. It contains information about the classification process (e.g., `classificationMethod`, `classificationProbability`) and a high-level type (`observationType`) to separate animal observations from (typically unwanted) other observations (blank, human, vehicle, unknown, and unclassified). Animal observations can further specify the scientific name, count, life stage, sex, behavior and identifier of the observed individual(s). Fields required for distance-sampling analyses and Random Encounter Modelling (Rowcliffe *et al.*, 2008; Howe *et al.*, 2017) are available as well (`individualPositionRadius`, `individualPositionAngle`, `individualSpeed`).

The table supports two common classification approaches: media-based and event-based (`observationLevel`). Media-based observations use a single media file as their source (`mediaID`). These are especially useful for machine learning and don't need to be mutually exclusive (e.g., multiple classifications of the same file are allowed). Event-based observations consider an event with a specified duration (`eventStart`, `eventEnd`) as their source and can comprise a collection of media files. These are especially useful for ecological research and analysis (Meek et al., 2014) and should be mutually exclusive, so that their count can be summed. In such ecological analysis, important parameters of many species abundance and density models (e.g., animal group size) can be reliably assessed (i.e., preventing under- and over-counts) by taking into account the context information of an entire sequence of consecutive camera trap records constituting an ecological event (*sensu* Meek et al., 2014). Note that media-based observations can be automatically aggregated into events using statistical functions or custom algorithms, but might under- or overestimate total group count (see Figure 1).

Media-based observations can further refer to a specific region of a media file where an animal or human was observed. A spatial region is expressed as a bounding box (`bboxX`, `bboxY`, `bboxWidth`, `bboxHeight`), specifying the x and y coordinates of the top-left corner of the bounding box and its width and height, respectively. All values are relative to the absolute width and height of the media file. A temporal region is expressed as two timestamps (`eventStart`, `eventEnd`), specifying the start and end times in a video file. These sub-media spatio-temporal regions can be used for machine learning applications (Beery et al. 2019), object tracking and behavior recognition.

To demonstrate the use of Camtrap DP, we included an example dataset (Desmet, Neukermans & Cartuyvels, 2022), versioned with the standard. Like any Camtrap DP dataset, its `datapackage.json` file references the version of Camtrap DP it should comply with. This allows the standard to evolve to new versions, archived datasets to remain valid and software implementations to understand how to interpret the data. Since the `datapackage.json` references the data files, it also allows to directly load remote data into a programming environment (Desmet & Oldoni, 2022; Oldoni & Desmet, 2022). Camtrap DP datasets can be transformed to species occurrence data expressed as Darwin Core Archives (Darwin Core Maintenance Group, 2021), as demonstrated by the `write_csv()` function in the “camtraptor” R package (https://inbo.github.io/camtraptor/reference/write_dwc.html; Oldoni & Desmet, 2022). Since Darwin Core is designed as a cross-domain biodiversity information standard (Wieczorek *et al.*, 2012), this transformation loses some information by design, both in width (excluding camera-trap-specific terms) and length (excluding non-animal observations, such as blank sequences).

Discussion

The increase in camera trap data and its availability offers not only exciting opportunities, but also important challenges to overcome. Thus far, camera trapping has not achieved its full potential for standardization, reuse and scaling-up from local to global spatial domains (Steenweg *et al.*, 2016). We think that facilitating the exchange of camera trap data can stimulate the creation of information that is critically needed to address relevant challenges in wildlife conservation and management. Through this publication, we provide a missing piece for the global camera trap data infrastructure, Camtrap DP, which we propose as a standard for exchanging camera trap data in a FAIR, open and both machine- and human-readable way. This data exchange standard enables the camera trapping community to take the next steps towards more collaborative and open research, using specialized software, big data, sophisticated image recognition algorithms and large cyber-infrastructures (Farley *et al.*, 2018).

The role of Camtrap DP

Camtrap DP will facilitate interoperable and robust data flow between all relevant global camera trap cyber-infrastructure components, offline databases, and individual participants (Hanke *et al.*, 2021). In this way, the possibility of frictionless harmonization of camera trap data produced by a globally distributed network of researchers and conservationists will help with "harnessing its collective power" (Hampton *et al.*, 2013) and addressing major environmental problems related to wildlife conservation and management.

One of the fundamental principles of Camtrap DP is its simplicity. This does not preclude its robustness in organizing tabular data and providing rich metadata content. This has been shown by several other data-intensive scientific communities where similar solutions (i.e., based on the Frictionless Data specification) have been developed and adopted in diverse scientific domains, e.g., electricity system modeling (Wiese et al., 2019), experimental life sciences (Jacob et al., 2020), marine microbiology (Ponsero et al., 2020), or the monitoring of a COVID-19 outbreak in India using a citizen-science approach (Ulahannan et al., 2020).

The demonstrated ability to derive Darwin Core species occurrence data from Camtrap DP makes it a suitable source for biodiversity data aggregation services such as the Global Biodiversity Information Facility (GBIF), which can further increase discoverability and reuse.

Since the Camtrap DP standard captures essential metadata about a camera trap study, it can also be used as a format to archive data in line with FAIR principles. FAIR publishing or archiving data on research repositories (e.g., Zenodo, DataOne, Dataverse, Figshare or Dryad) prevents data loss and facilitates reuse, and is increasingly demanded by funders and journals. Sensitive data can be obscured if necessary (see Lennox *et al.*, 2020). For example, access to images of threatened species can be restricted, deployment coordinates can be obscured or roughly indicated, and people names can be replaced with anonymous identifiers.

Camtrap DP can also stimulate the development of standardized camera trap data processing pipelines, including those focused on the application of Artificial Intelligence/Machine Learning methods for automatic image recognition (Tabak *et al.*, 2018; Kellenberger *et al.*, 2020) and the automation of camera trap data analysis using already well-established statistical frameworks for modeling, e.g., species distribution, species richness, activity patterns, occupancy and abundance (Rovero & Zimmermann, 2016; Wearn & Glover-Kapfer, 2017). Apart from one valuable initiative, https://lila.science, most of the publicly available camera trap datasets that could be used to train AI models remain fragmented, difficult to find and have low accessibility.

Camtrap DP will facilitate creating and publishing open, harmonized, findable and easily accessible datasets of annotated images and videos of wildlife species recorded in different ecosystems worldwide. The findability and interoperability will enable camera trap data to be harvested from public or private API endpoints (e.g., from GBIF, Zenodo or camera trap data management systems) and processed in high-performance cloud computing environments.

How does Camtrap DP extend the Camera Trap Metadata Standard (CTMS)?

The Camtrap DP development has been based upon an open, collaborative and community oriented approach, which should reduce the risk of becoming outdated with no maintenance and versioning, as is unfortunately occurring for CTMS (Forrester *et al.*, 2016). Similar to Darwin Core (Wieczorek *et al.*, 2012), we envision Camtrap DP as a community-driven and evolving standard. This flexibility seems to be especially important given rapid development in ecological and conservation technology, with camera trapping not being an exception.

Camtrap DP builds upon the first effort to standardize camera trap data (CTMS) in important ways. It structures the data in a simple yet flexible data model, contains equivalents of all CTMS fields for which use cases were found, adds new fields to capture more information about deployments, media (e.g., their file location) and observed species (e.g., sex and life stage). It supports the expression of observations at the level of (ecological) events (Meek *et al.*, 2014; sequence in CTMS), media and sub-media (e.g., detected objects encompassed by bounding boxes). This approach better enables the development and training of AI models (media-level) as well as ecological analysis (event-level). Animal observations include fields for animal sex, life stage, behavior, individual identifier and more. Rather than a single file (JSON or XML in CTMS), data is organized in a descriptor file (JSON) for dataset/project-level metadata and tables for deployments, media and observations. We recommend the use of CSV files, but any other serialization format supported by Table Schema (including JSON) is valid. Data tables are linked together via foreign keys, thus mimicking the structure of relational database system (Fowler *et al.*, 2018).

Camtrap DP is based on a well-established framework and it comes with a suite of open source software tools in multiple programming languages to create, validate and read camera trap data packages. The JSON schemas enable validation of dataset metadata, structure, required fields and compliance of values with controlled vocabularies, another important improvement over CTMS.

Is Camtrap DP FAIR?

As Camtrap DP is directly derived from the Frictionless Data specification it automatically inherits most of the basic principles of FAIRness (Wilkinson *et al.*, 2016), https://www.go-fair.org/fair-principles). For example, principles supported out-of-the-box include the possibility to assign a globally unique and persistent identifier to the dataset and each data record (Findability: fair principle "F1"), Profile and Table Schemas describing all (meta)data properties with rich metadata (Findability: "F2", "F3"; Reusability: "R1"), access to all elements of the dataset over http (Accessibility: "A1"), and the possibility to clearly define a dataset license (Reusability: "R1.1"). The Interoperability principles are supported by the package descriptor concept, which uses an accessible, shared, broadly applicable and machine-readable format (JSON) and vocabularies (JSON schemas) to describe package metadata and its specification. The latter has a great potential for new extensions. Moreover, the CSV format is a well-established, simple, compact and machine-readable standard for storing and exchanging tabular data. Camtrap DP extends the base support for the FAIRness principles provided by the Frictionless Data specification in the following manner:

- Findability ("F") and Reusability ("R"). We include three dataset-level terms to indicate spatial, temporal and taxonomic coverage. The latter is especially useful since camera trapping datasets often contain a large amount of so-called by-catch data (Scotson et al., 2017).
- Accessibility ("A"). Allowing data to be shared with or without the access to original media files provides more granular levels of accessibility.
- Interoperability ("I"). Term equivalents from other standardized vocabularies (Darwin Core, Dublin Core, Audiovisual Core, Data Cite Metadata Schema) are indicated whenever applicable using Simple Knowledge Organization System (SKOS) identifiers such as `skos:exactMatch`.
- Reusability ("R"). Reusability is further bolstered by proposing Camtrap DP as a domain-relevant community standard ("R1.3") for camera trap data and by including package-level metadata such as project ownership, published references and sampling methodology ("R1.2").

Extending Camtrap DP

Through open collaborative development and version tracking, Camtrap DP can be easily improved or extended in response to feedback from the camera trapping community. Suggestions for new fields or tables can be proposed through the GitHub issue tracker. An example of a potential extension of Camtrap DP is the integration of a separate table for animals that can be identified at the individual level using physical features such as distinct fur, feather or skin patterns or even using facial recognition algorithms (Vidal *et al.*, 2021). Similarly, an extra table with detailed descriptions of animal behavior captured by camera trap videos could be considered in future releases and incorporated into the core Camtrap DP structure when agreed by the community.

However, Camtrap DP also comes with a built-in extension mechanism that allows users to add additional information to the core structure of a data package themselves and remain compliant with the standard. This can be achieved by defining new Resources in a data package descriptor file, adding the corresponding data files to the data folder, and defining a JSON schema for each new resource. For example, adding an extra attribute describing the health condition of observed animals would involve creating a table `health.csv`, adding it as a new resource to `datapackage.json` and defining a new schema with the first column being a foreign key to the `observations.csv` table and the second providing categorical or numerical information about the health status of the observed individual. This new table would then be automatically validated by Camtrap DP along with the core tables.

Moreover, we also believe that Camtrap DP provides a solid basis for further application in semi(automated) media capture by sensors that are not fixed in one location (e.g., mounted on drones, autonomous underwater vehicles, etc).

Facilitating adoption of Camtrap DP

Community-wide adoption of a data standard requires implementation by existing systems and applications. Many authors of this paper are maintainers of software tools used by the camera trapping community, which should facilitate the adoption of Camtrap DP. On the production side, it is critically important that camera trap data management systems add support for Camtrap DP as an export format. Agouti and Trapper have already done so, and Wildlife Insights, eMammal and the R package “camtrapR” all officially support the development and release of Camtrap DP, with plans to incorporate seamless conversion between Camtrap DP and their native data formats. The R package “camtraptor” (Oldoni & Desmet, 2022) was developed to facilitate the consumption of Camtrap DP. It provides functionality to read, explore, filter, transform and visualize Camtrap DP datasets, and aims to support the combination of datasets for cross-study analyses and closer integration with “camtrapR”. The publication of Camtrap DP datasets is supported by the Global Biodiversity Information Facility (GBIF) and has been implemented as a data publication format in the forthcoming version 3 release of their Integrated Publishing Toolkit (IPT; Robertson *et al.*, 2014; GBIF Secretariat, 2022). Using the IPT, researchers can now upload their camera trap data, transform it to the standard, document it with metadata using a graphical user interface, publish the dataset as a Camtrap DP and register it with GBIF for harvesting and increased findability.

Equally important to software implementation, is building trust within a community towards a proposed solution (Urbano *et al.*, 2021). This can be achieved by an open, collaborative and community-oriented development process (Wieczorek *et al.*, 2012) and active promotion within the existing networks of camera trap data producers (Urbano *et al.*, 2021). The support from trusted and well-recognized organizations can also be of critical importance. We hope to facilitate that trust by developing Camtrap DP under the umbrella of the Biodiversity Information Standards (TDWG), a non-profit organization dedicated to developing biodiversity information standards and responsible for maintaining well-known and commonly used standards such as Darwin Core or Audiovisual Core. Through TDWG we can also seek community review and ratification as a standard. Through outreach and collaboration, Camtrap DP is now supported by GBIF and recommended by GigaScience Press as the submission format for camera trap data in their journals GigaScience and GigaByte.

Finally, it is worth noting that by using the Camtrap DP data exchange format, users are by no means forced to make their datasets publicly available. Camtrap DP is designed to facilitate data exchange between researchers and institutions and to ensure that the data can be easily shared and reused in the future. However, the decision to make the data publicly available is entirely up to the data owner. This can be especially important, e.g., for long-term camera trap studies and researchers who are open to sharing their datasets with others on request, but are not willing to publish their data in an open access mode (Mills *et al.*, 2015).

A common data model for camera trap data

While Camtrap DP answers the need for a data exchange model and format, it would be good if it was underpinned by a comprehensive data model for the whole camera trapping domain - one that models and defines all domain-relevant concepts, can fully capture datasets without redundancy, ambiguity or partiality, cross-references terms and synonyms, and can act as a rosetta stone for users of different management systems, thus facilitating the translation of data to Camtrap DP. Although such a comprehensive Camtrap Data Model (Camtrap DM) is not the subject of this paper, its in-depth analysis and description are planned for future publication.

Conclusions

The rapid generation of large and harmonized camera trap datasets, together with the development of standardized and accessible AI-driven data processing pipelines, will allow ecologists to learn more about wildlife community ecology, including human-wildlife coexistence across large-scale ecological gradients of human pressure and landscape configuration. Conservationists and policy-makers can capitalize on this knowledge to make informed science-based management decisions and encourage cooperation between countries, engaging in dialogue with stakeholders (wildlife managers, farmers, NGOs, policy makers) and promoting best practices in wildlife management methods.

As technological innovations in camera trapping continue at a rapid pace, many camera trap research teams face significant challenges when managing, classifying, re-using and sharing datasets that often contain thousands of media files. Using efficient infrastructure and tools at hand, the data from various camera trap projects can be harmonized and integrated to address scientific and conservation goals. As an open, evolving standard for the FAIR exchange and archive of camera trap data, Camtrap DP represents an important step towards a global data sharing workflow with rapid results and thus more timely science-based wildlife management recommendations.

Data availability

Camtrap DP version 1.0 <doi> (Intended to be a Zenodo deposit of the Camtrap DP GitHub repository, but pending review and release of v1.0. See https://github.com/tdwg/camtrap-dp for the current version.)

Supplementary material

Camtrap DP version 1.0 - Human-readable documentation (Intended to be a pdf version of the Camtrap DP website, but pending review and release of v1.0. See https://tdwg.github.io/camtrap-dp/ for the current version.)

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Author contributions

JWB and PD conceived the initial idea for Camtrap DP (conceptualization) and supervised and coordinated its development (supervision, project-administration); JWB, BN, DO, DS, JC, JN, JW, MR, MT, PAJ, SJB, TDF, TR, TRH, YL and PD contributed to the development of Camtrap DP (methodology, validation); JWB, DO, JN, MR, TR, YL and PD coordinated software development in support of Camtrap DP (software); JWB, TM, and PD acquired funding in support of Camtrap DP (funding-acquisition); PD created the example dataset (data-curation), website and figure (visualization); JWB, BN and PD wrote the initial draft of the manuscript (writing-original-draft). All authors contributed critically to the drafts and gave final approval for publication (writing-review-editing).

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