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APPLICATION

camtrapR: an R package for efficient camera trap data management

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Summary

1. Camera trapping is a widely applied method to study mammalian biodiversity and is still gaining popularity. It can quickly generate large amounts of data which need to be managed in an efficient and transparent way that links data acquisition with analytical tools.

2. We describe the free and open-source R package camtrapR, a new toolbox for flexible and efficient management of data generated in camera trap-based wildlife studies. The package implements a complete workflow for processing camera trapping data. It assists in image organization, species and individual identification, data extraction from images, tabulation and visualization of results and export of data for subsequent analyses. There is no limitation to the number of images stored in this data management system; the system is portable and compatible across operating systems.

3. The functions provide extensive automation to minimize data entry mistakes and, apart from species and individual identification, require minimal manual user input. Species and individual identification are performed outside the R environment, either via tags assigned in dedicated image management software or by moving images into species directories.

4. Input for occupancy and (spatial) capture–recapture analyses for density and abundance estimation, for example in the R packages unmarked or secr, is computed in a flexible and reproducible manner. In addition, survey summary reports can be generated, spatial distributions of records can be plotted and exported to GIS software, and single- and two-species activity patterns can be visualized.

5. camtrapR allows for streamlined and flexible camera trap data management and should be most useful to researchers and practitioners who regularly handle large amounts of camera trapping data.

Key-words: biodiversity surveys, camera trapping, data management, detection history, monitoring, occupancy models, photo trapping, spatial capture–recapture models, wildlife studies

Introduction

Camera trapping is a powerful and widely used method for the rapid assessment of mammalian biodiversity, particularly in challenging environments (Tobler *et al.* 2008; Sunarto *et al.* 2013; Burton *et al.* 2015). A multitude of ecological analyses utilize camera trap data, including estimation of occupancy probabilities (MacKenzie *et al.* 2002) or abundance, density and demographic rates with capture–recapture (Karanth 1995; Silver *et al.* 2004) and spatial capture–recapture models (Efford 2004; Royle *et al.* 2009; Gardner *et al.* 2010). These methods are implemented in R packages [e.g. unmarked (Fiske & Chandler 2011), secr (Efford 2015) or RMark (Laake 2013)] and stand-alone computer programs [e.g. program MARK (White & Burnham 1999) or PRESENCE (Hines 2006)].

Efficient use of these analytical tools requires efficient and systematic management of the large numbers of images that can be generated in short periods of time. A variety of approaches using different software have been developed for that purpose (Harris *et al.* 2010; Fegraus *et al.* 2011; Sundaresan, Riginos & Abelson 2011; Sanderson & Harris 2013; Krishnappa & Turner 2014; Tobler 2014; Zaragozí *et al.* 2015; McShea *et al.* 2016; Ivan & Newkirk 2016; see the latter and Table S1 for a comparison of approaches). These software approaches have different foci and offer different sets of features. In developing camtrapR, we aimed at incorporating and expanding upon these capabilities within a unified camera trap data management tool. In addition to functionalities already available (e.g. automatic import of images, generation of reports and input files for subsequent analyses), camtrapR (i) uses the increasingly popular R language, (ii) is free and fully open-source, (iii) is fully compatible with Windows, MacOS and Linux, (iv) reads and allows the user to create arbitrary image

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metadata tags, (v) supports different methods for identifying species and individuals and (vi) has mapping and GIS export capabilities.

Here, we describe camtrapR, the first toolbox for the management of camera trap data available for the R community. Our R package provides a flexible and coherent workflow for efficient camera trap data organization, exploration and processing in the R statistical language, which seamlessly connects data acquisition with downstream analytical tools. We outline the camtrapR workflow for organizing camera trap images as well as extracting, exploring and visualizing the resulting data and illustrate its use with a sample data set from a camera trapping study conducted in Sabah, Malaysian Borneo (Mohamed *et al.* 2013). Detailed vignettes, help files, sample data and analyses are available in the camtrapR package available on CRAN (https://cran.r-project.org/web/packages/camtrapR/).

Functionality

The camtrapR standard workflow can be divided into five main functionalities, listed here and described in sequence below.

1. *Image organization and management:* Setting up a directory structure for storing raw camera trap images and optionally renaming images by station identity (station ID), date and time.

2. *Species/individual identification:* Species and individual identification by metadata tagging in image management software or drag and drop of images into directories. Functions for checking species lists with taxonomic databases, verifying identification and appending species names to files are provided.

3. *Image data extraction:* Tabulation of species records and extraction of image metadata.

4. *Data exploration:* Visualization of spatial species occurrence patterns (including export to GIS software), single- and two-species activity patterns.

5. *Data export:* Preparation of input files for subsequent analyses in occupancy and (spatial) capture–recapture frameworks. Generation of survey summary reports.

Table 1 provides a list and a short description of all functions in the camtrapR package. The functions of the package are described below and in more detail in the package help files and vignettes.

Package description

OVERVIEW

The camtrapR package, now in version 0.99.1, is written in the R language (R Core Team 2015) and was first released on CRAN in July 2015. It can be used under R version 3.1 (R Core Team 2015) and higher on Windows, MacOS and Linux. The key functions of the package make use of the free command line software ExifTool (Harvey 2015) via system calls to extract metadata from camera trap images in JPEG format. camtrapR provides extensive automation of processes, performs rigorous consistency checks on input data and has no inherent limitation in terms of the image number held in the data management system.

camtrapR was designed for studies utilizing arrays of camera trap stations, each consisting of one or more (often two) camera trap units (termed cameras for sake of simplicity). Cameras within a station are set in relative proximity to each other compared to between-station distances.

Table 1. List of camtrapR functions

Functionality	Function	Description
Image organization and management	*createStationFolders*	Create directories for storing raw camera trap images
	timeShiftImages	Apply time shifts to JPEG images
	imageRename	Copy and rename images based on station ID and image creation date
	appendSpeciesNames	Add or remove species names from image filenames
Species/individual identification	*checkSpeciesNames*	Check species names against the ITIS taxonomic database
	createSpeciesFolders	Create directories for species identification
	checkSpeciesIdentification	Consistency check on species identification
	getSpeciesImages	Gather all images of a species in a new directory
Image data extraction	*recordTable*	Create a species record table from camera trap images
	recordTableIndividual	Create a single-species record table from camera trap images with individual IDs
	exifTagNames	Return metadata tags and tag names from JPEG images (for use in *recordTable* functions)
	exiftoolPath	Add the directory containing exiftool.exe to PATH temporarily
Data exploration and visualization	*detectionMaps*	Generate maps of observed species richness and species detections by station
	activityHistogram	Plot histograms of single-species activity
	activityDensity	Plot kernel density estimations of single-species activity
	activityRadial	Radial plots of single-species activity
	activityOverlap	Plot two-species activity overlap and compute activity overlap coefficient
Data export	*cameraOperation*	Create a camera operation matrix
	detectionHistory	Species detection histories for occupancy analyses
	spatialDetectionHistory	Detection histories of individuals for spatial capture–recapture analyses
	surveyReport	Summarize a camera trapping survey

IMAGE ORGANIZATION AND MANAGEMENT

Image organization begins with saving raw images into camera trap station directories (e.g. myStudy/rawImages/stationA). Station directories may contain camera subdirectories (e.g. myStudy/rawImages/stationA/camera1) if more than one camera was used at a station. The function *createStationFolders* can create these directories.

Date and time of images can be changed using the function *timeShiftImages*, for example if internal camera date and/or time values were set incorrectly, reset accidentally, or if users wish to synchronize camera pairs. It uses the date/time shift module of ExifTool.

If desired, all images can be renamed automatically with station ID, camera ID, date and time with the function *imageRename*.

IMAGE METADATA AND METADATA TAGGING

Digital images contain metadata in standardized Exif format, for example date and time, geotags, camera settings, ambient data, trigger event number and many more. In addition, users can assign information to images via custom metadata tags in image management software, for example species or individual identification, sex, behaviour, group size counts or group membership of individuals. These metadata tags become part of the images and are portable without depending on a relational database structure. Both types of metadata can be extracted, tabulated and used subsequently, for example for data filtering prior to analyses. The package vignettes contain a performance estimate for metadata extraction using ExifTool.

We recommend the free and open-source software DigiKam (www.digikam.org) for tagging because it provides a customizable, hierarchical tag structure and has powerful filtering, querying and batch-tagging capabilities. Adobe Lightroom and Adobe Bridge are also suitable.

SPECIES IDENTIFICATION

Species identification is a laborious but most crucial step in the workflow because all analyses rely on correct species identification and many models are sensitive to false positives (Miller *et al.* 2011). It is also the only task that cannot be automated readily (both in this and other software packages), as automatic identification tools are currently still too unreliable and need reference data for all species potentially present in the study area (Yu *et al.* 2013; but see McShea *et al.* 2016). `camtrapR` supports two different ways of identifying species: (i) by assigning species tags to images in image management software, and (ii) by moving images into species directories [drag and drop, an approach also used by Harris *et al.* (2010) and Sanderson & Harris (2013)].

Users are free to use any species names (or abbreviations or codes) they wish. If scientific or common species names are used, the function *checkSpeciesNames* can check them against the ITIS taxonomic database (www.itis.gov) and returns their matching counterparts (utilizing the R package `taxize` (Chamberlain & Szöcs 2013) internally), making sure species names and spelling are standardized and taxonomically sound, and thus making it easier to combine data sets from different studies.

To improve reliability of species identification, multiple observers can replicate species assignment (if metadata tags are used for species identification). In order to reconcile their species assignments, and because of the scope for incorrect species assignment even by one observer, the function *checkSpeciesIdentification* finds conflicting species assignments from multiple observers and assesses temporal proximity between images assigned to different species within the same station.

After species identification, the function *appendSpeciesNames* optionally appends species names to file names. The function *getSpeciesImages* can create a species image report by copying all images of a focal species into a separate species directory (e.g. myStudy/speciesImages/Malay Civet), thus facilitating checks on species identification or gathering images for expert identification. If species identification changes at a later point (e.g. after expert identification), these images can easily be copied back into the image directory structure and functions can be rerun.

INDIVIDUAL IDENTIFICATION

Individual identification is a prerequisite for spatial (as well as traditional, non-spatial) capture–recapture analyses. After identifying images to species level and collecting images of the focal species, individual identification is performed in the same way as species identification described above, using either metadata tags or directories for individual identification.

IMAGE DATA EXTRACTION

After species identification, the function *recordTable* organizes species records in a table containing (at the minimum) station IDs, species names, date and time of records (see Table 2). The function *recordTableIndividual* offers analogous capabilities for individually identified animals. In order to use the capabilities of `camtrapR` on record tables from prior work (created manually or with other software), these data sets can easily be converted into the simple data format provided by the *recordTable* functions.

Both functions can extract custom and manufacturer-specific metadata tags from the images. Because metadata tag names are generally unknown, the function *exifTagNames* returns metadata tags and tag names, thereby helping users to identify the relevant tags they wish to include in the tables.

A filter for temporal independence between images of the same species at the same station is implemented (argument `minDeltaTime`, in minutes). If set to 0, the *recordTable* functions return all records. Any higher number will only return records that were taken at least `minDeltaTime` minutes after the last record of the same species/individual at

Table 2. Example record table. *Station* is the camera trap station ID, and *Species* are Leopard Cat *Prionailurus bengalensis* (PBE) and Malay Civet *Viverra tangalunga* (VTA). '*delta.time*…' denotes the lag between a record and the last record of the same species at the same station (in seconds, minutes, hours and days). Columns *Directory* and *FileName* were omitted

Station	Species	DateTimeOriginal	Date	Time	delta.time.secs	delta.time.mins	delta.time.hours	delta.time.days
StationA	PBE	2009-04-21 00:40:00	2009-04-21	00:40:00	0	0	0·0	0·0
StationA	PBE	2009-04-22 20:19:00	2009-04-22	20:19:00	157140	2619	43·6	1·8
StationA	PBE	2009-04-23 00:07:00	2009-04-23	00:07:00	13560	226	3·8	0·2
StationA	PBE	2009-05-07 17:11:00	2009-05-07	17:11:00	1270920	21182	353·0	14·7
StationA	VTA	2009-04-10 05:07:00	2009-04-10	05:07:00	0	0	0·0	0·0
StationA	VTA	2009-05-06 19:06:00	2009-05-06	19:06:00	2296740	38279	638·0	26·6

the same station or, alternatively, `minDeltaTime` minutes after the last independent record of the same species/individual. All functions for downstream analyses depend on the results of *recordTable*/*recordTableIndividual* and thus on the argument `minDeltaTime`.

CAMERA TRAP STATION INFORMATION

A simple data frame is used to store information about camera trap stations and, if applicable, individual cameras (see Table 3). It contains station/camera IDs, geographic coordinates, setup and retrieval dates, and possibly station-level covariates. It can be created in standard spreadsheet software and imported into R. Periods in which cameras malfunctioned (once or repeatedly) can be defined. Both format and names of date and coordinate columns can be specified by the user.

Based on setup, retrieval and malfunctioning dates, the function *cameraOperation* computes a day-by-station camera operation matrix, coding whether stations were operational, partly operational, not operational (malfunctioning) or not set up. The camera operation matrix reflects the daily trapping effort per station, that is the number of active cameras per station and day. Depending on their placement, multiple cameras within a sampling point can increase the probability of detecting an animal. If cameras are set up directly opposite each other, they may be considered one operational unit. If they are set up further apart, it may be desirable to count them as two units accumulating effort independently. Therefore, the camera operation matrix can return either the number of operational cameras (if effort is accumulated independently) or an indicator for station operability (if effort is not accumulated independently). The camera operation matrix is used in creating detection histories for occupancy and spatial capture–recapture analyses (see description of the functions *detectionHistory* and *spatialDetectionHistory* below).

DATA EXPLORATION AND VISUALIZATION

`camtrapR` can plot maps of species records (number of observed species by station and number of independent detections by species; see Fig. 1) with the function *detectionMaps*. The function allows shapefile export for use in GIS software. Single-species activity patterns can be visualized in three different ways: as histograms of hourly activity, activity kernel density estimations and radial plots (functions *activityHistogram, activityDensity* and *activityRadial*). Two-species activity overlaps (Ridout & Linkie 2009) are estimated and plotted with the function *activityOverlap*. These functions use code from the packages `overlap` and `plotrix` (Meredith & Ridout 2014; Lemon *et al.* 2015).

DATA EXPORT FOR OCCUPANCY ANALYSES

Occupancy models are used to gain insight into species habitat associations while accounting for imperfect detection. The function *detectionHistory* computes species detection/non-detection matrices for use in occupancy models, for example in package `unmarked` (Fiske & Chandler 2011) or program PRESENCE (Hines 2006) by combining the record table created with the function *recordTable* and the camera operation matrix created with the function *cameraOperation*. In the detection/non-detection matrices, rows represent stations and columns survey occasions. Survey occasions consist of one or more days. The matrix cell becomes 1 if a species was detected at a station during an occasion, 0 in case of non-detection, and NA if the station was not operational. Users have complete freedom over occasion start dates and time, occasion length (in days) and the length of the trapping period per station. Occasions can begin on a fixed date, the day the first station was set up or each station's individual setup date (optionally with a

Table 3. Example camera trap station table. *Station* is the camera trap station ID, *utm_y utm_x* are station coordinates. *setup_date* and *retrieval_date* are the dates the stations were set up and retrieved. *Problem1_from* and *Problem1_to* define malfunctioning dates

Station	utm_y	utm_x	setup_date	retrieval_date	Problem1_from	Problem1_to
StationA	604000	526000	02/04/2009	14/05/2009		
StationB	606000	523000	03/04/2009	16/05/2009		
StationC	607050	525000	04/04/2009	17/05/2009	12/05/2009	17/05/2009

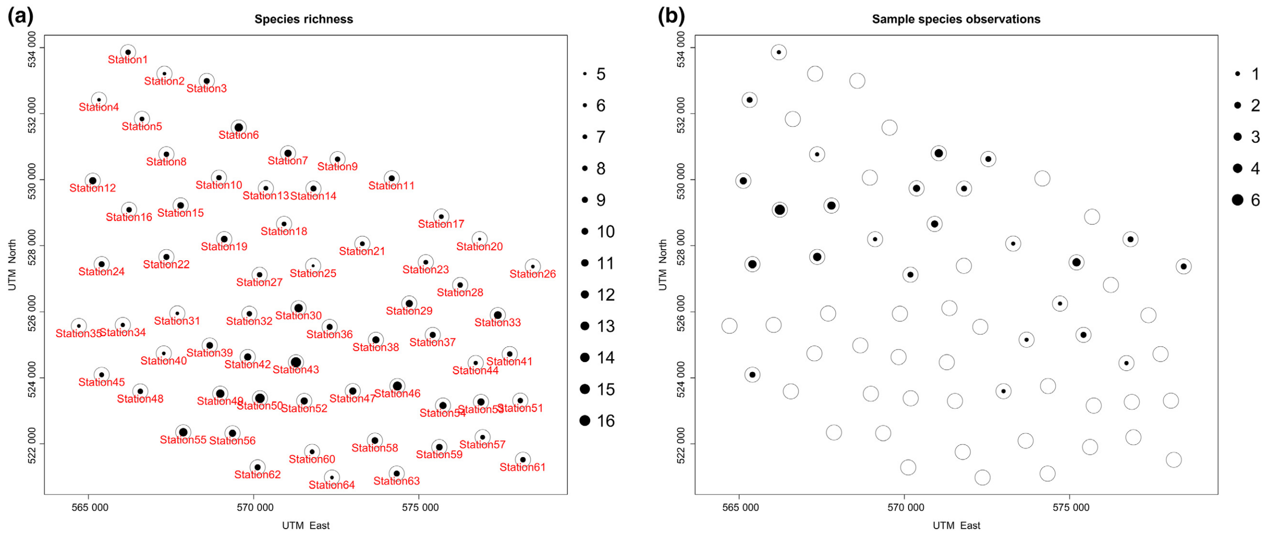

Fig. 1. Example maps created with the function *detectionMaps*. (a) Number of observed species. (b) Number of independent observation of an example species.

buffer between the setup date and the beginning of the first occasion).

Trapping effort by station and occasion can be returned alongside species detection histories for use as a covariate/offset on detection probability. Incomplete occasions (occasions in which cameras were only partly operational) may contain records in the detection/non-detection matrix if effort is returned. Otherwise, any incomplete occasion will cause corresponding detection matrix cells to be NA.

DATA EXPORT FOR (SPATIAL) CAPTURE–RECAPTURE ANALYSES

Spatial capture–recapture methods use repeated detections of marked individuals of a species at an array of sampling locations (camera trap stations) to estimate species density while accounting for imperfect detection and movement of individuals about their home ranges (Efford 2004; Royle & Young 2008; Royle *et al.* 2014). In order to prepare species data for spatial capture–recapture analyses, the function *spatialDetectionHistory* can build `capthist` objects as defined in the `secr` package (Efford 2015), containing information about where (station) and when (occasion) individuals were detected. The camera trap station table, the camera operation matrix and the record table are combined for that purpose. The record table needs to contain individual IDs (see sections Individual Identification and Image Data Extraction) and may contain individual covariates (from metadata tags). The stations' geographic coordinates and station-level covariates are read from the camera trap station table. The camera operation matrix provides information about station operation dates and trapping effort. In creating the `capthist` objects, we provide the same flexibility regarding occasion length and starting time as in the function *detectionHistory*. Trapping effort (trap usage) can also be returned in the `capthist` object. For non-spatial capture–recapture analyses, the function can also return an `RMark` data frame, containing only individual-by-occasion information without the spatial component.

CREATING A SURVEY REPORT

The function *surveyReport* summarizes camera trapping surveys. It returns station operation and image date ranges, the number of trap days (total and by station), observed numbers of species and the number of independent observations by species and station. A zip file containing essential data and tables, detection maps and activity plots can be generated. It also contains an example script for reproducing all of these and for creating the input for occupancy analyses. The summary report and zip file can further be used for data sharing and archiving, for example in online repositories such as the Knowledge Network for Biocomplexity (KNB; https://knb.ecoinformatics.org/).

Conclusion

`camtrapR` is the first R package to bridge the gap between camera trap data acquisition and the well-developed downstream analytical tools by providing a workflow for camera trap data management, exploration and preparation of subsequent analyses. Its main advantages are flexibility, ease of use, extensive automation of many of the otherwise labour-intensive tasks, and compatibility with software for further analyses of camera trapping data.

`camtrapR` offers a standardized camera trap data management, and we expect it to be most useful to researchers and practitioners who regularly handle large numbers of camera trap images and wish to generate input for activity, occupancy and/or (spatial) capture–recapture analyses with minimal manual effort. We will keep improving and extending `camtrapR` functionalities and welcome both feedback and collaborations to further increase the usefulness to its users.

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Data accessibility

The `camtrapR` package is available from CRAN on https://cran.r-project.org/web/packages/camtrapR/. It includes detailed vignettes, help files, sample data and code examples. This article does not use any data.

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Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

Table S1. Comparison of software for camera trap data management.