Camera traps as sensor networks for monitoring animal communities

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Abstract—Studying animal movement and distribution is of critical importance to addressing environmental challenges including invasive species, infectious diseases, climate and land-use change. Motion sensitive camera traps offer a visual sensor to record the presence of a species at a location, recording their movement in the Eulerian sense. Modern digital camera traps that record video present new analytical opportunities, but also new data management challenges. This paper describes our experience with a year-long terrestrial animal monitoring system at Barro Colorado Island, Panama. The data gathered from our camera network shows the spatio-temporal dynamics of terrestrial bird and mammal activity at the site - data relevant to immediate science questions, and long-term conservation issues. We believe that the experience gained and lessons learned during our year long deployment and testing of the camera traps are applicable to broader sensor network applications and are valuable for the advancement of the sensor network research. We suggest that the continued development of these hardware, software, and analytical tools, in concert, offer an exciting sensor-network solution to monitoring of animal populations which could realistically scale over larger areas and time spans.

I. INTRODUCTION

The movement of organisms through their environment lies at the heart of ecological field research and is of critical importance to addressing environmental challenges including invasive species, infectious diseases, climate and land-use change. Movement is the key defining characteristic of most animals, and there are two basic ways to record animal motion [1]. The Lagrangian approach monitors a specific organism, for example with a GPS tag, and records a series of locations it passes through. The Eulerian approach, on the other hand, monitors a specific location and records the movement of all organisms across it. Animal trackers following the Lagrangian approach have been tracking animal movement since the advent of radio-telemetry [2]. While useful for many purposes, these individual tracking studies are limited by the difficulty and bias associated with capturing animals, as well as the logistical complications of tracking over long periods or large areas. Camera traps offer a Eulerian solution to monitoring animals that avoid these biases by simply recording a photograph of the animals that move in front of them.

Distributed, motion-sensitive cameras (aka camera traps) are examples of sensor networks that can collect data on animal populations. This paper develops the concept of camera traps as a network of distributed sensors to monitor animal communities, using a year-long case study from Barro Colorado Island (BCI), Panama. The developed system uses existing camera technology to capture a unique and unbiased picture of environmental dynamics for medium and large size terrestrial animals. In the remainder of this section we give a background of camera traps and describe the specific study objectives. In Section II we describe the overall hardware and software infrastructure followed by study design and methodology in Section III. In Sections V, VI we describe several practical aspects of deploying and testing a real-world camera networks.

A. Basic Advantage of Camera Traps

All animals move, but most are shy and quite. Camera traps are an appropriate technique for animal monitoring for the following reasons: (1) Non-invasive: by only capturing photographs with invisible IR flashes, camera traps have no effect on animal behavior. (2) Low labor: camera traps are easy to deploy and can function for weeks with no attention. (3) Robust data: photographs are analogous to museum specimens in being a permanent record of date, location, and species. (4) Bonus material: in addition to recording the presence of a species camera traps can record animal behavior which can be important for scientific questions, but also offers engaging images useful for education and promotion.

B. General Scientific Uses for Camera Trap Data

At the most basic level, camera trap data can be used to prove the existence of a species at a site; with sufficient effort, it can also suggest the absence of a species. This could be important to show the arrival of an invasive species, or document the survival or extinction of rare species [3], [4]. Multiple georeferenced locations for a species can further be used to document their distribution in an area, and compare with environmental features to create models of distribution or resource selection [5]. Local animal density, the gold standard for animal monitoring, can also be estimated from camera trap data, given proper study design [6], [7]. These data become more valuable as they accumulate across sites or over years, for example showing predator-prey relationships of tigers across India [8] and documenting their population demography at one site for 9 years [9].

C. Specific Objectives of our Camera Trap Study

We are using camera traps to survey the diversity and abundance of the mammal and terrestrial bird communities on BCI. In addition to the general objectives (mentioned in Section I-B), we are also interested in comparing these communities in areas with different abundances of food. Using aerial photographs and on-the-ground mapping of palm trees [10] we have identified 5 low-fruit and 5 high-fruit 1ha plots. We are comparing levels of animal diversity, activity and abundance in these plots using cameras deployed in random locations within the plots. We use 2 cameras per plot, moving them to new locations each 8 days. We followed this protocol for 1 full year from 22 January 2008 to 21 January 2009. We...
are also studying other things about these plots, chief among them, radio-tracking agoutis and the seeds they disperse. In addition to this the experimental setup allows us to look at the effect of food on animals.

D. Novel Aspects of Our Study

Over last few years, wireless sensor networks have been used extensively for ecological monitoring applications [11]–[17]. However, to the best of our knowledge this is the first year-long camera trap deployment in a real-world setting (rainforest on BCI) that uses novel camera deployment strategies and systematically reports back practical and theoretical lessons learned, both from science and sensor network research viewpoint. Following are the key differences between our work and the existing research.

Traditional camera trap studies used film cameras to study one particular target species. This led to the development of techniques that maximize their efficiency of photographing that species, but may decrease the detection of others (e.g. using baits or targeting tiger trails). Our study aimed to document the entire terrestrial mammal community, and therefore modified protocols to minimize bias and detect any and all animals passing in front of a camera’s sensor. Four aspects of our protocols are therefore different than most other camera studies: randomizing camera deployment locations, using no bait, monitoring year-round, and recording video sequences for each trigger.

Additionally, our study was designed to focus camera deployments within 10 study plots to compare animal communities between sites with different amounts of fruit. More general monitoring protocols would probably alter this slightly to spread the cameras out more.
Additionally, year-round monitoring may be overkill for some research objectives. However, we advocate that randomizing camera locations and setting without bait are important protocols that should be employed by any study trying to document entire animal communities.

II. INFRASTRUCTURE

Our field work was conducted at the Barro Colorado Island (BCI) (9°10′N, 79°51′W) research station, which is managed by the Smithsonian Tropical Research Institute. BCI is a completely forested, 1567 ha island was formed when Lake Gatun was created as part of the Panama Canal. Animals continue to move between the island and the surrounding National Park land, which are separated by a few 100m at various places. The island receives an average of 2632 mm of rain per year. The meteorological year is divided into two parts: a pronounced dry season (approximately from mid-December to the end of April), and a wet season (May to mid-December). Relative humidity, soil moisture, air pressure, solar radiation, evapotranspiration, wind speed and direction all show marked wet/dry season differences. On the other hand, temperature varies relatively little throughout the year [18].

A. Camera Hardware Requirements:

The components of a camera trap sensor network are simple in being a collection of camera traps which are deployed in the field, a series of memory cards used to record images and transfer them back to the lab, and a database to save and organize images and metadata. Wireless transmission of images is possible, but not practical in most situations. Live transmitting of data is limited by the battery power needed to send 100s of images from a remote camera, not to mention limited communication networks in many wild areas.

Camera trap studies do not typically require high-resolution images, but do have a number of minimum requirements needed to collect robust and unbiased data (Table I). Because they are typically deployed for long periods of time in harsh conditions, they must be incredibly well protected from rain and humidity (e.g., BCI is a rainforest with prominent a wet season). Most modern digital cameras can capture night-time images using IR flashes, which can not be seen by animals. This is an important feature because a visible flash is a source of potential bias for a camera trap study if animals are disturbed by the flash and avoid the camera thereafter [19]. Digital cameras with infrared flashes should result in neither aversion nor curiosity, although their flashes may still be visible by people if viewed directly.

We are using Reconyx RC55 digital camera traps with 1 Gb compact flash cards for image storage. Two cameras were deployed simultaneously at random locations within each of 10 1-ha plots. To compare this randomized protocol with traditional trail-side sets we also deployed a subset of cameras along trails near our plots (ref. Figure 1(a)). We used a GPS (Garmin 60CSx) to locate these points in the field and then mounted cameras on the nearest tree at a height of 20 cm. The camera view was maximized by aiming them in the most suitable direction, with the least vegetation or slope obstructing their view within 5-10m. Cameras were programmed with the following settings: low-resolution (1 mega pixel) pictures at a frame rate of approximately 1 fps and trigger was set to no-delay mode. They were also programmed to also make time-lapse pictures every 12 hours in order to check proper functioning.

We scheduled camera deployments to be 8 days, whereupon the camera was moved to a new location. Most analyses are done across camera sites, so decreasing the duration of each deployment to increase the number of sites surveyed is preferred. However, increasing
### Table I

**Hardware Requirements for Our Application of Remote Cameras as Sensor Network to Monitor Animal Populations**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motion Sensor</td>
<td>5-10m range</td>
</tr>
<tr>
<td>Flash</td>
<td>Infrared</td>
</tr>
<tr>
<td>Camera</td>
<td>IR sensitive camera for night pictures, color for day</td>
</tr>
<tr>
<td>Picture resolution</td>
<td>1 megapixel sufficient, higher is better</td>
</tr>
<tr>
<td>Picture rate</td>
<td>1 frame per second allows video</td>
</tr>
<tr>
<td>Battery life</td>
<td>Depends on photo and flash rate, 2-5+ weeks typical on 6 C-cell batteries</td>
</tr>
<tr>
<td>Trigger time</td>
<td>1/10th second, longer will miss animals passing by</td>
</tr>
<tr>
<td>Memory</td>
<td>1gb compact flash cards usually sufficient, more needed for longer deployments or higher resolution photos</td>
</tr>
<tr>
<td>Cost</td>
<td>$500 now, cheaper is better</td>
</tr>
</tbody>
</table>

(a) Camera Settings used by our study.

(b) The daily activity pattern for one nocturnal and one diurnal animal species.

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Fig. 3. Camera Settings and Daily Activity Patterns for BCI study

the number of days at a site will increase the precision of the estimate of passage rate, and also detect more rare species. Areas with lower mammal density than BCI should use longer camera deployments, 2-4 week-long deployments are typical in other studies [21]. This trade-off can be statistically modeled to help fine tune a study-design to meet specific research objectives [22].

We now briefly describe our data management infrastructure. After 8 days of deployment, we swap the memory cards in cameras with blank memory cards and return the used memory cards to the lab where images are organized in a custom-made MySQL database with a PHP web interface. Time, date, trigger event, trigger type and camera are automatically extracted from the metadata of the images (exif data). Data is organized per plot, location, camera run and card run (Figure 2(a) shows the the conceptual overview of the database and not the details due to space constraints.)

Because we record sequences of images consecutively (pseudo-video), we have to separate or join sequences before analyzing animal passage rates. Our basic goal is to have each sequence represent one individual or social group of animals. We consider any pair of sequences separated by more than 40 minutes to be different, and any less then 30 seconds apart to be the same. Consecutive sequences with 00:30 to 40:00 between them are flagged and checked manually to determine if they should be split or lumped. The final step of data processing is to identify the contents of each image sequence. We register the species present and register the number of animals. For species that are identifiable by unique coat patterns, such as ocelots or paca, we also note each animals individual ID. Figure 2(b) shows a sample clip that will be processed using the above procedure.

### IV. Statistical Analysis

Camera trap data is analyzed in three main ways. First, details of the animals represented by each photo sequence are available including the species, group size, date, time, and location. This data is useful for showing
the overall frequency of detection of each species and the temporal distribution of activity (Figure 3(b), Figure 4).

Second, details of the animals detected at each camera location are calculated. The simplest estimate is a detection rate over the entire camera deployment, recorded as the total number of sequences of a given species divided by the total time a camera was running. This is useful as a general measure of abundance that may also be used to estimate true animal density [6]. A slightly more complicated query outputs the performance of each camera on each day it was in operation in terms of the detection or non-detection of a given species. This data is analyzed to calculate the probability of detection for a given site, which can be further developed in occupancy modeling, taking into account various environmental covariates [22].

Third, the capture histories of individual animals can be analyzed using mark-recapture protocols. This is typically possible for a subset of species that have unique coat markings such as spotted jaguars or striped tigers [7], but may also be applied to male ungulates with unique antler patterns [23] or to other species tagged with unique color markings [24].

V. EXPERIMENTAL RESULTS

A. Forest Signatures

Our year-long deployment of remote cameras at randomized locations has given us a unique and unbiased view of the overall activity of animals on the rainforest floor including the species present and their relative abundance (Figure 4). The deployment resulted in a total of 764 deployments with 17111 animal detections and 25 species detections. This measure of animal activity is simply the number of times a given species walked across a sample plot, and offers direct metric of potential ecological impact. For example, as shown in Figure 4, on BCI agoutis, peccaries, and paca are the most frequently detected species, and thus the most likely to have an impact on local plant populations through seed predation or dispersal. If calibrated into density (animals/km²) [6] these could also be used to derive estimates of biomass for each species or ecological group.

The standardized measures of species diversity and abundance represented by these signatures (Figure 4) are exactly those needed to evaluate the effects of modern environmental change. Effects of climate change and invasive species would be reflected in changes in species composition, while changes in abundance would reflect natural population fluctuations, as well as more dramatic crashes or explosions typical of human influenced dynamics.

B. Sample Size Optimization

Our year-round survey is unique in offering a seasonal view on the animal community. However, many basic objectives of estimating the diversity and abundance of the community can be met with less effort. We used our year-round data set to evaluate the sample size needed to meet these objectives. Figure 5(a) shows the relationship between estimated mammalian species diversity and sampling effort. Each deployment represents one camera in the field for 8 days, and levels off after 15-25 deployments. There are 19 large and medium-sized terrestrial mammal species theoretically possible on BCI, although 4 of these (jaguar, jaguarundi, margray, and grison) are very rarely recorded on BCI, probably only as sporadic visitors.

We also evaluated the sampling intensity needed to obtain an accurate estimate of detection frequency, an index of animal abundance (Figure 5(b)). This shows that the variation in average agouti detection rate levels off after 15-20 camera deployments, suggesting this is an appropriate sample effort. This could be met, for example, with 15 8-day deployments of one camera, or 3 deployments of 5 cameras. This relationship varies across species, with accurate estimates for species that are rare, or variable in their activity, requiring more sample effort.

C. Camera Deployments Strategies

Traditionally camera traps are deployed at sites known to have high animal activity, such as along a trail or near a water body, to maximize the detections of target species. Although other studies have shown differences between the activity of animals on trails compared with non-trails [25], few studies have employed a truly randomized protocol [6].

We found that there was a significant difference between the trap rate at randomized sets compared with trail-side sets for five of the most common mammal species (Mann-Whitney U Test, p < 0.05, randomized n = 667, trail-side n = 71). Some species (agoutis, ocelots) were detected more often on trails, while others (paca, collared-peccary, red-brocket deer) appear to avoid trails. Thus, the trail-side cameras appear to be giving a biased view of the animal community compared with randomized locations.

D. Camera performance in real-world

Due to challenging weather and environmental conditions camera traps are often more difficult to operate in rainy reasons.

We found a surprising effect There was a strong effect of seasonality Figure 6(a) with detection distance shortening during the rainy season. This is probably a combination of moisture on the sensor, in the air between the sensor and the target, and on the target itself. Together, these would dampen the difference between the IR signature of an animal compared with the background, and thus reduce its ability to detect an animal. Shrinking the effective area each camera surveys has obvious impacts on the number of animals it detects. Thus it is important to document these effects, and take them into account for comparisons of animal activity across seasons or sites. In addition, our experience shows that cameras malfunction more during rainy season compared to that of a dry season.
(a) Frequency of detection for 25 species of terrestrial birds and mammals on BCI.

(b) The daily pattern of animal activity on the forest floor. Colors match the species names in Fig 4(a).

Fig. 4. Forest signatures from camera trap deployment at BCI

(a) Each camera deployment represents 8 days of monitoring. Curves are drawn using a rarefaction (Sobs) or Jackknife (Jack1) resampling of 200 camera deployments on BCI.

(b) The variation in estimated detection rate for agoutis with sampling effort. The mean rate (black line) changes little, but the variation (min/max are thin red lines, 95% confidence intervals are thick red lines) in estimates decreases with increasing sample effort, leveling off after around 15-20 camera deployments. All estimates come from 1000 resamples of data from one study plot.

Fig. 5. Sample Size Optimization Study Results
To minimize the impact of seasonality on camera performance we suggest use of zorb-it silica desiccant packets (2 if possible) to keep the insides dry. We also advise to keep cameras in dry-closet whenever not in use. Based on our experience rotating cameras out of service every 2 months for preventative maintenance works well.

E. Camera failures in real-world

We observed that only 30% of the deployed cameras never failed during the year (Figure 6(b)). This shows that operating a camera trap based solution over extended periods of time does require monitoring and debugging. Approximately 40% failures were due camera lens being blurry. The manufacturer repaired all cameras, and used our experience to find that the problem was caused by humidity de-laminating a filter on the lens. They have since improved the seal on the lens. The second major source of failures was (-20%) caused by humidity affecting circuitry of the camera. The manufacture has since developed a new coating for their circuit boards which should improve their performance in high humidity.

VI. PRACTICAL CONSIDERATIONS AND EXPERIENCES

A. Equipment Management:

Although we are hopeful that improved designs will be more weather-proof, we expect that hardware maintenance will remain a critical aspect for any long-term monitoring project. Key items to regularly inspect and service include the rubber gaskets that prevent moisture from entering system components, exposed metal contacts and battery leads (for corrosion and dirt), and external wires. In humid environments, care should be taken when moving cameras from air-conditioned rooms into field conditions because condensation will form on electronic parts and lenses. Finally, it is important to be realistic about the durability of remote cameras and to prepare for equipment malfunction. We advise that researchers not deploy every available remote camera but rather have a few extra units at the ready to replace broken equipment. When working in particularly challenging environments, maintaining a reserve of cameras amounting to 20% of the total number deployed may be necessary to maintain consistent sampling effort.

B. In field Equipment Testing

Determining the optimal frequency at which to check each camera station usually entails a tradeoff between maximizing efficiency and ensuring that stations will remain functional during the entire sampling interval. Numerous factors, including the type of camera system (e.g., film versus digital), camera programming (e.g., camera delay), whether sets are baited or unbaited, and expected site activity level, must be considered. Based on our experience, we recommend checking new camera sets within 7-14 days and then judging when to return next based on the condition of the battery and memory reserves in that first period.

C. Minimizing theft:

In this project we had minimal risk of theft because of the high security on BCI. However, this is a potential problem for many distributed sensor networks, including camera traps. Minimizing the detection of your camera by others is the first measure to take to reduce theft. Running cameras off-trail and below eye-level helps this. A visible flash also gives away the location of your camera, so digital cameras with IR flashes should be more cryptic. Units with a red filter over the flash further reduce risk by eliminating even the dull red glow of IR flashes. A simple cable and padlock should deter most thieves. A small sign taped to the side of the camera...
b briefely describing the purpose of the study and providing relevant contact information typically satisfies curiosity and limit vandalism. However, no lock is foolproof to a determined thief with the right tools, so studies should anticipate some level of theft by having replacement cameras on hand.

VII. FUTURE WORK AND CONCLUSION

A. Scalable Image Analysis Framework

The hardware and data management protocols we outline here are appropriate for most research objectives set by typical camera-trap projects, and they easily handle the hundreds of cameras and few tens of thousands pictures we have been generating in one year. However, expanding this type of monitoring much above this level to cover multiple sites or larger areas, with more cameras, would cause new problems with data management and storage. First, our current manual approach of visual inspection of video images/clips would become a time-limiting step if the rate of image acquisition increased and would not scale well. To that end, we have started investigating automated image analysis techniques. Our preliminary tests showed promising results for automated species detection (which will be published separately). Second, we are in addition exploring how to harness the power of cloud computing for our application. In particular, we are building a scalable image analysis framework based on open source software tools such as Apache Pig [26] and Apache Hadoop [27]. We believe this would be an interesting future direction for our project.

At present, the cameras are not networked and the data retrieval is non-realtime (by manual retrieval of memory cards) due to energy and environmental constraints. However, in future, we plan to explore the option of real-time data transmission by networking the field deployed cameras. This will allow us to study various interesting system level issues such as data transmission reliability and energy consumption.

To conclude, data gathered from our a year-long terrestrial animal monitoring system at Barro Colorado Island, Panama shows the spatio-temporal dynamics of terrestrial bird and mammal activity at the site - data relevant to immediate science questions, and long-term conservation issues. We believe that the experience gained and lessons learned during our year long deployment and testing of the camera traps are applicable to broader sensor network applications and are valuable for the advancement of the sensor network research.

REFERENCES