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Towards the automated detection and occupancy estimation of primates using passive acoustic monitoring

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ABSTRACT

Recent advancements in technology have made possible the use of novel, cost-efficient biomonitoring techniques which facilitate monitoring animal populations at larger spatial and temporal scales. Here, we investigated using passive acoustic monitoring (PAM) for wild primate populations living in the forest of Taï National Park, Côte d'Ivoire. We assessed the potential of using a customized algorithm for the automated detection of multiple primate species to obtain reliable estimates of species occurrence from acoustic data. First, we applied the algorithm on continuous rainforest recordings collected using autonomous recording units (ARUs) to detect and classify three sound signals: chimpanzee buttress drumming, and the loud calls of the diana and king colobus monkey. Using an occupancy modelling approach we then investigated to what extent the automated, probabilistic output needs to be listened to, and thus manually cleaned, by a human expert, to approach occupancy probabilities derived from ARU data fully verified by a human. To do this we explored the robustness of occupancy probability estimates by simulating ARU datasets with various degrees of cleaning for false positives and false negative detections. We further validated the approach by comparing it to data collected by human observers on point transects located within the same study area. Our study demonstrates that occurrence estimates from ARU data, combined with automated processing methods such as our algorithm, can provide results comparable to data collected by humans and require less effort. We show that occupancy probabilities are quite robust to cleaning effort, particularly when occurrence is high, and suggest that for some species even naïve occupancy, as derived from ARU data without any cleaning, could provide a quick and reliable indicator to guide monitoring efforts. We found detection probabilities to be most influenced by time of day for chimpanzee drums while temperature and, likely, poaching pressure, affected detection of diana monkey loud calls. None of the covariates investigated appeared to have strongly affected king colobus loud call detection. Finally, we conclude that the semi-automated approach presented here could be used as an early-warning system for poaching activity and suggest additional techniques for improving its performance.

1. Introduction

As concern for the current biodiversity crisis grows and the loss of species continues, conservationists and researchers struggle to find practical solutions for regularly monitoring wild animal populations that may be under threat or especially vulnerable to human disturbance. Recent technological advances have opened up the domain of biomonitoring to new methods and tools that have great potential for real-time applications such as early-warning systems in areas where there is human–wildlife conflict (Zeppelzauer et al., 2014); or to alert field workers of increased anthropogenic stress to populations (Wrege et al., 2010; Penone et al., 2013), including poaching pressure (Wrege et al., 2012) or changes in populations due to natural causes such as disease and dispersal. In the last decade, autonomous audio–visual devices have gained popularity due to their ability to non-invasively collect objective data on wild animals with minimal human disturbance (Kühl and Burghardt, 2013). However, the increased popularity of autonomous recording units (ARUs), especially their potential for longitudinal monitoring with relatively little additional cost, has created the need for

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more sophisticated automated methods of handling the large audio datasets they produce (Blumstein et al., 2011; Wimmer et al., 2013; Kühl and Burghardt, 2013).

Passive acoustic monitoring (PAM) is a non-invasive method for surveying wild animals using remote acoustic technologies such as microphone arrays, hydrophones, or other autonomous recording devices (Blumstein et al., 2011; Marques et al., 2013). PAM has already proven useful for monitoring taxa at large geographic scales or species that are rare or elusive, particularly for birds (Swiston and Mennill, 2009; Celis-Murillo et al., 2012; Oppel et al., 2014), cetaceans (Mellinger et al., 2007; Van Parijs et al., 2009), insects (Riede, 1998; Penone et al., 2013), bats (Walters et al., 2012), and even forest elephants (Wrege et al., 2012). With over 50% of all primate species threatened by extinction (Mittermeier et al., 2009), methods which aid in long-term monitoring of primate populations would be a useful asset for conservationists working to protect some of the last strongholds of threatened wild populations. This was our principal objective in applying PAM for primates, to contribute to the research on automated biomonitoring techniques in hopes of improving the limited temporal and spatial scope of existing methods.

Automated methods for capturing sounds of interest from continuous audio recordings have proven problematic with many acoustic monitoring studies still using human experts to detect calls of interest in the data (Wrege et al., 2012; Wimmer et al., 2013; Penone et al., 2013). This is largely because of the variability in the signal-to-noise ratio of sounds captured on ARUs due to two principal reasons: distance of the source animal from the device and the variation in background noise levels in the environment. Despite these difficulties, recent studies have demonstrated considerable advancement in the automated detection of species-specific calls from continuous field recordings made in the field for birds (Digby et al., 2013), insects (Chesmore and Ohya, 2004), elephants (Zeppelzauer et al., 2014), cetaceans (Mellinger and Clark, 2000), and bats (Walters et al., 2012). Additionally, an impressive multi-species system for a tropical rainforest was recently proposed (Aide et al., 2013). However, it is often unclear whether the same data was used for training and testing which can considerably inflate performance statistics when conducting algorithm evaluations.

The rainforest provides a particularly challenging environment for passive acoustics. The background noise level is on average high and varies dramatically over the course of a day (Waser and Waser, 1977), of which the consequence is a high false positive and false negative rate. This is the central impediment to developing species-specific algorithms for automated sound detection since human experts are much better at discriminating between a call of interest from high background noise (Blumstein et al., 2011). However, the error associated with human detection and classification is rarely quantified although it can considerably bias results and lead to inappropriate inferences (Guschanski et al., 2009; Miller et al., 2011; Kühl and Burghardt, 2013; Digby et al., 2013). At the very least then, automated approaches allow for this error in detection and classification to be a known quantity, which can then be accounted for statistically when drawing inference from the data. Still, it remains that, due to the complex soundscape found in terrestrial ecosystems, few customized automated acoustic approaches exist for land mammals. Nevertheless automated systems have the potential to provide real-time data on animal populations and thus would be an invaluable tool for wildlife managers (Blumstein et al., 2011; Aide et al., 2013).

Occupancy probability is the probability that a species is present at a site and is the most basic unit of information field practitioners can use to study and monitor wild populations (MacKenzie et al., 2006). It requires fewer assumptions than estimating abundance when using indirect cues such as vocalizations, and addresses the central problem in PAM of failing to detect a species when it is actually present, also known as imperfect detection probability (MacKenzie et al., 2002). To our knowledge, this is the first study to apply an automated detection and classification algorithm specifically aimed at primate vocalizations to determine occupancy probabilities of multiple species. Bat researchers, for which there exists commercially available software for automated species detection and recognition of calls, have similarly estimated occupancy probability for conservation implications using automated data collection (Yates and Muzika, 2006; Hein et al., 2009). For PAM to be applicable as a primate biomonitoring tool in the field, we created a system where the input data were continuous ARU recordings of the forest, and the output was a short audio clip associated with a probabilistic vocal class assignment; thereby not including any human intervention until the moment of validation and interpretation (for a detailed description of the algorithm see Heinicke et al., in press).

Our primary aim was to examine to what extent the automated algorithm output must be manually validated or 'cleaned' by a human expert in order to provide reliable information about primate species occurrence that could be used to guide field practitioners. Specifically, we investigated whether occupancy probabilities derived using an occupancy modelling framework improved naïve occupancy estimates for the ARU data, and compared this to human point transect data from the same area. Additionally, we assessed the influence of environmental covariates on vocalization detection probability at ARUs. Moreover, we investigated how robust our occupancy probability estimates were to using the automated output by simulating datasets with varying degrees of cleaning for false positives and false negatives in the ARU data. Finally, we interpret our findings to provide recommendations on how the current method could be applied as an early-warning system, and suggest improvements on how to enhance algorithm performance and optimize data collection for future surveys.

2. Materials and methods

2.1. Study site and data collection

The study was conducted in the rainforest of the Taï National Park, Côte d'Ivoire (for details see Boesch and Boesch-Achermann, 2000). From November 2011 through May 2012, 20 Wildlife Acoustics SM2+ ARUs were systematically placed within an area of 35–45 km^2 (Fig. 1) which encompassed the territories of two habituated chimpanzee (*Pan troglodytes verus*) communities, south and east group (Kouakou et al., 2011). There are also eight diurnal monkey species inhabiting Taï forest, including the diana monkey (*Cercopithecus diana*), red colobus (*Procolobus badius*), and the black and white colobus, also known as the king colobus (*Colobus polykomos*) (McGraw and Zuberbühler, 2007). Of the nine primate species present at Taï, we focussed on only a subset of three species (chimpanzee, diana monkey, and king colobus) due to limitations in development (i.e., lack of sufficient training data for the other primates), and performance of the automated sound recognition algorithm for primate vocalizations used in this study (also see Section 2.1.2). The Taï chimpanzees regularly engage in hunting red colobus monkeys, the most frequently hunted prey item, as well as king colobus, the second most hunted prey item (Boesch and Boesch-Achermann, 2000). The chimpanzees are rarely observed to hunt diana monkeys probably because they exhibit a high degree of vigilance (Boesch and Boesch-Achermann, 2000, McGraw and Zuberbühler, 2007). The territories of the chimpanzee communities were 26.5 km^2 for the south group and 30.1 km^2 for the east group (Kouakou et al., 2011) with 25 and 34 individuals (including dependent offspring), respectively, at the end of the study period. The monkeys are also territorial but have overlapping home ranges