Global Ecology and Conservation 16 (2018) e00493

Contents lists available at ScienceDirect

Global Ecology and Conservation

journal homepage: http://www.elsevier.com/locate/gecco

Review Paper

Pairing camera traps and acoustic recorders to monitor the ecological impact of human disturbance

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ARTICLE INFO

Article history:
Received 7 September 2018
Received in revised form 27 November 2018
Accepted 27 November 2018

Keywords:
Acoustic monitoring
Anthropogenic disturbance
Biodiversity
Cameras
Community structure
Inventory and monitoring
Multiple stressors

ABSTRACT

Over the past two decades, the use of camera traps and acoustic monitoring in the investigation of animal ecology have grown rapidly, with each technique enhancing broad-scale wildlife surveying. Camera traps are a cost-effective, noninvasive means of sampling communities of mid-to large-terrestrial species, and acoustic recording devices capture human sounds and sound-producing animals, including species of mammals, birds, anurans, and insects. Rarely are these techniques combined, despite the advantages of merging their respective strengths. Namely, camera traps paired with acoustic recorders can evaluate the abundance, distribution, and behavior of multiple guilds and trophic levels across landscapes while concurrently monitoring multiple human stressors in real time. Moreover, integrating these approaches enhances detection accuracy and strengthens statistical inference at multiple survey scales. We conducted a literature review, and found only 13 studies that combine camera traps and acoustic recorders, 8 of which either compared the ability of each technique to detect species of interest or discussed the advantages of each technique. We outline potential questions that can be addressed by pairing acoustic recorders and camera traps, including enabling the simultaneous assessment of noise pollution and its impacts on mammal and avian communities. Furthermore, we discuss how the analysis of data from each technique face similar challenges; thus, simultaneous innovation offers the ability to apply solutions to both techniques and amplify their respective strengths. Digital technologies and big data are changing nature conservation in increasingly profound ways and integration of camera traps and acoustic recorders will facilitate new, transformative discoveries to meet modern conservation challenges.

1. Introduction

Natural ecosystems have been degraded by human disturbance, leading to unprecedented rates of biodiversity loss and altered functioning of entire ecosystems (Tscharntke et al., 2012). Monitoring human impact, predicting future change, and formulating effective mitigation actions across many components of biodiversity is a pressing challenge. Effective technologies and approaches to address this challenge are increasingly needed.

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https://doi.org/10.1016/j.gecco.2018.e00493

Attempts to monitor human impacts typically focus on the direct effects of a disturbance on individual species at limited scales, hindering our ability to understand the dynamics of large-scale ecological processes. Moreover, although species interactions are fundamental forces structuring ecological communities, surveys largely overlook broader interactions (McCann, 2007). Understanding how anthropogenic disturbance alters structural properties of an ecological community is challenging, requiring long-term monitoring of the distribution and abundance of animals at different trophic levels over large spatio-temporal scales. Additionally, as human development and activity continues to expand, novel disturbances - such as light and noise pollution - have become nearly ubiquitous (Gaston et al., 2015; Buxton et al., 2017b). Disentangling how multiple types of disturbance interact and prioritizing the mitigation of each component is problematic using conventional survey techniques (Burton et al., 2014).

To meet these monitoring challenges, ground-deployed autonomous technology offers a promising means to establish broad-scale, holistic monitoring systems that can integrate local and global ecological data (Turner, 2014). New technologies can expand the scale of ecological inference, capturing patterns in animal communities across vast geographic areas over long periods of time (Marvin et al., 2016). Moreover, rapid advances in computing have transformed the ability to collect, analyze, store, and share data in enormous volumes and at faster speeds (Snaddon et al., 2013), with novel applications for real-time monitoring and assessments (Wall et al., 2014). The collection of continuous data on wildlife patterns across years and biomes has revolutionized our understanding of ecology, ushering in a new era of big data and macrosystems ecology (Porter et al., 2009; Soranno and Schimel, 2014). Here we propose that pairing two well-developed and widely used technologies, camera traps and acoustic recorders, is an effective approach to monitor a myriad of global conservation threats and discuss how their integration and subsequent generation of big data offers new opportunities in ecology.

Large networks of camera traps and acoustic recorders are respectively collecting biodiversity data globally (Steenweg et al., 2017; Buxton et al., 2018). Technological advances in both hardware and software have streamlined the use of each method, and machine learning approaches have revolutionized the types of information extracted from such data and the speed with which processing occurs (Valletta et al., 2017). Pairing these technologies represents a unique opportunity to evaluate community structure and species distribution while monitoring multiple anthropogenic stressors in real-time. Both methods capture permanent records of animal behavior, abundance, and diversity and human activity (Pettorelli et al., 2010; O'Connell et al., 2011). Because both methods are automated, they remove confounding effects of human observer disturbance, reduce bias due to variation in observer ability, and thus collect standardized data that are replicable across time and space (Acevedo and Villanueva-Rivera, 2006). Importantly, both are cost-effective methods of monitoring biodiversity at ecologically meaningful spatio-temporal scales. We summarize each method, review studies that combine them, outline future applications, and discuss research needs to combine these tools to assess anthropogenic disturbances.

1.1. *Camera traps*

Autonomously triggered cameras (or camera traps) are effective at sampling terrestrial communities of medium to large mammals and birds near the ground (Fig. 1; Srbek-Araujo and Chiarello, 2005; O'Brien and Kinnaird, 2008). Camera traps can confirm the presence of nocturnal, rare, and cryptic species by monitoring continuously while removing the intrusive effects of human observers (Pettorelli et al., 2010). Moreover, camera traps can be used to derive insights into morphology, behavior, phenology, activity, habitat use, distribution, abundance, and population dynamics of specific species (O'Connell et al., 2011). By detecting a range of species, camera traps can be used to examine community assemblages and interspecific interactions. Given enough camera stations and sampling duration, researchers can examine the ecological complexity of systems (Nichols et al., 2011) or discover new species (Dang et al., 2001).

The use of remote cameras has grown rapidly in the past decade, including efforts to develop long-term monitoring stations globally to ascertain population trends of a suite of species across numerous ecosystems (Steenweg et al., 2017). Global initiatives that combine data sets across large spatial and temporal extents (e.g., eMammal https://emammal.si.edu/ and the Tropical Ecology Assessment and Monitoring Network www.teamnetwork.org) can provide the statistical power to ascertain trends in rare species (Lynam et al., 2013) and provide indices to monitor biodiversity (Buckland et al., 2005; O'Brien et al., 2010). Camera trapping is also an important tool to understand landscape dynamics (e.g., vegetation phenology; Sonnentag et al., 2012) and the effects of human disturbance (Caravaggi et al., 2017). Use of camera traps to quantify human presence and activities on landscapes is increasing with the aim of better understanding the influence of human activities on wildlife communities. In addition, camera traps and their application have been successfully used to assist law enforcement efforts in protected areas (Hossain et al., 2016).

1.2. *Passive acoustic monitoring*

Animals produce sounds for a number of biological functions (Brumm, 2013). Recording sound in a habitat (known as passive acoustic monitoring), can capture the diversity and abundance of vocalizing and sound-producing animals (Fig. 1). Birds in particular are regularly surveyed by sound, and acoustic recordings have been suggested as a suitable alternative to point counts (Sedláček et al., 2015), often detecting higher numbers of species than observer methods (Acevedo and Villanueva-Rivera, 2006). Acoustic monitoring of a range of vocal animals has been applied to assess species phenology (Willacy et al., 2015; Buxton et al., 2016), diversity (Riede, 1998; Sueur et al., 2008), behavior (Tyack and Clark, 2000; Russo and Jones, 2003; Lynch et al., 2015), abundance (Flaquer et al., 2007; Borker et al., 2014), population dynamics (Oppel et al.,

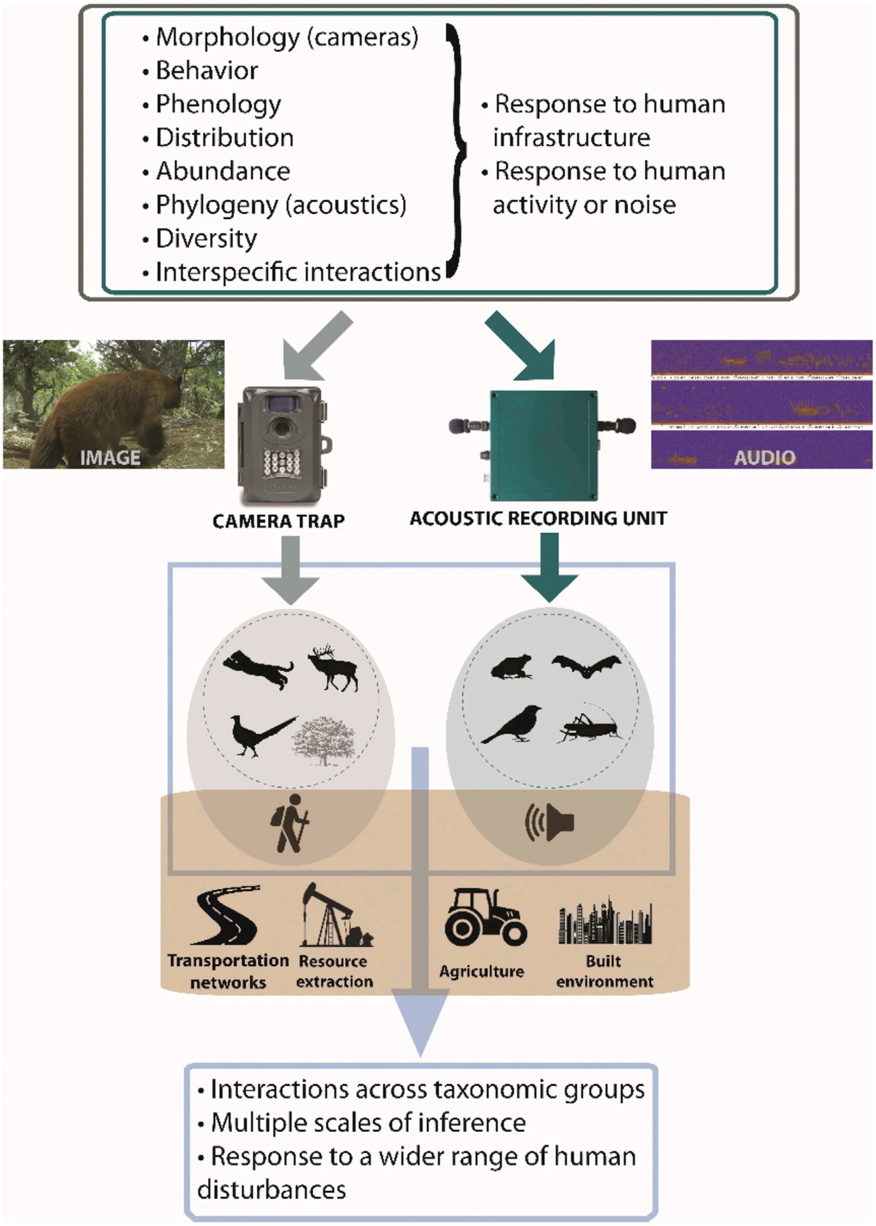

Fig. 1. Independently, camera traps and acoustic recorders can capture a variety of biological metrics. Camera traps typically target terrestrial animals (e.g., carnivores, ungulates, birds near the ground) and can assess habitat condition (e.g., plant phenology), whereas acoustic recorders capture vocal species (e.g., anurans, bats, birds, invertebrates). Paired camera traps and acoustic recorders can compensate for detection biases of either technique, amplifying the number of species monitored and allowing for an expanded assessment of community structure and interactions among taxa at multiple scales. Moreover, each technique captures a separate aspect of anthropogenic disturbance (e.g., transportation networks, resource extraction, agriculture, and infrastructure), where camera traps capture the presence, type, and intensity of human activity and acoustic recordings capture noise. Thus, combining techniques can enable a more comprehensive understanding of the impacts of human disturbance on different groups of species. Green arrows indicate monitoring using acoustic recordings, grey arrows indicate monitoring using camera traps, and the blue arrow and boxes indicates monitoring combining the two technologies. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2014), and distribution (Dawson and Efford, 2009). Recordings have facilitated the discovery of new species (Tishechkin, 2014) and the study of phylogenetic relationships (Goicoechea et al., 2010). Arrays of microphones enable the study of animal movement on a small scale or locating animals and tracking their dispersal on a larger scale (Blumstein et al., 2011). Finally, acoustic monitoring can quantify rates of human activity in real-time, such as logging, hunting, or poaching, providing valuable information for protected area management and anti-poaching (Wall et al., 2014; Linder et al., 2016).

Rapid advances in cost-effective digital recording technology has ushered in a new era for acoustic ecology, allowing monitoring at many locations over long, coordinated time periods. This new approach, where sampling operates across landscapes and ecological gradients, can target communities and ecological processes, rather than particular species or populations (Buxton et al., 2018). This draws from new fields: soundscape ecology, which examines all sounds emanating from a given landscape (Pijanowski et al., 2011), and ecoacoustics, where sound is examined along a broad range of spatial and temporal scales to measure biodiversity and ecosystem functioning (Sueur and Farina, 2015). Moreover, large-scale acoustic monitoring provides a measure of anthropogenic noise, which is now recognized as a pervasive ecological threat, masking acoustic cues and eliciting behavioral responses (Shannon et al., 2016). Because of its diffusive nature and expansive impact, the study of noise pollution requires monitoring at large spatio-temporal scales (Buxton et al., 2017b).

2. Current state of integration

In May 2018 we conducted a systematic survey of the literature to identify papers that integrated the use of camera traps and acoustic monitoring for wildlife research from 1990 to 2018. We searched Web of Science using camera trap* AND acoustic* or camera trap* AND noise* as topics. All searching and filtering was conducted by the same individual (RTB). We found 118 results which were appraised by title and then abstract for inclusion. We excluded marine studies using active acoustics ($n = 8$) and studies only using one technology ($n = 11$). We also consulted studies referencing the identified literature for additional resources. We found a total of 13 relevant papers (Table 1). Six of these studies examined terrestrial mammals other than bats (e.g., squirrel gliders *Petaurus norfolcensis*) and six occurred in the United States. All studies were published after 2011, and 12 were published within the past four years. The majority of studies ($n = 8$) were methodological, comparing the ability of each technique to detect a species of interest, discussing the utility of each technique, or developing statistical methods to analyze the data from each technique.

Four studies pairing camera traps and acoustic monitoring examined the impact of human disturbance, including aircraft, noise and light pollution, and wind turbines on species behavior and abundance (Derose-Wilson et al., 2015; Francis et al., 2015; Robinson et al., 2015; Buxton et al., 2017a, Table 1). In one case, thermal cameras captured the distance, velocity, and bearing of birds and bats near a wind turbine while acoustic recorders measured activity and abundance and identified species (Robinson et al., 2015), with the aim to minimize collision mortality. Only one study used camera traps and acoustic monitoring to study biotic interactions (Table 1; Isbell and Bidner, 2016). This study used acoustic recorders to measure the properties of vervet monkey (*Chlorocebus pygerythrus*) calls at sleeping sites and used cameras to monitor the approach of leopards (*Panthera pardus*), finding that vervet monkeys produce specific ‘leopard alarm calls’ and that leopards approach closer at night when monkeys produce fewer alarm calls (Isbell and Bidner, 2016). We note that although few published

Table 1
Literature review of papers combining passive acoustic and camera trap monitoring, including the location of the study, taxonomic group examined, and type of study (i.e., methodological, investigating biotic interactions, or examining the impact of human disturbance).

Reference	Application	Location	Taxonomic Group	Type of study		
				Methods	Biotic interactions	Human impacts
Waldon et al., 2011	Monitor biodiversity in Reduced Emissions from Deforestation and Degradation (REDD) projects	n/a	Multi-species	Y		
Derose-Wilson et al. (2015)	Examine the response of Wilson's plovers (*Charadrius wilsonia*) to different types of aircraft	North Carolina, USA	Birds			Y
Francis et al. (2015)	Influence of noise and light pollution and other urban features on squirrel gliders (*Petaurus norfolcensis*)	Australia	Terrestrial mammal			Y
Horton et al., 2015	Compare detection biases for capturing spatial and temporal patterns in nocturnal flying animals	Delaware, USA	Terrestrial mammal	Y		
Lucas et al. (2015)	Develop methods to model animal density	n/a	Multi-species	Y		
Robinson et al. (2015)	Examine the collision rate of birds and bats with offshore wind facilities	USA	Birds and bats			Y
Diggins et al. (2016)	Compare methods to detect Carolina northern flying squirrel (*Glaucomys sabrinus coloratus*)	North Carolina, USA	Terrestrial mammal	Y		
Isbell and Bidner (2016)	Examine predator-prey dynamics of vervet monkeys (*Chlorocebus pygerythrus*) and leopards (*Panthera pardus*)	Kenya	Terrestrial mammal		Y	
Buxton et al., 2017a,b	Examine the response of Brandt's cormorants (*Phalacrocorax penicillatus*) to different types of aircraft	California, USA	Birds			Y
Enari et al., 2017	Compare methods to detect sika deer (*Cervus nippon*)	Japan	Terrestrial mammal	Y		
Gorresen et al., 2017	Compare methods to detect hoary bats (*Lasiurus cinereus*)	Hawaii, USA	Bats	Y		
Rayment et al., 2017	Compare methods to detect right whales (*Eubalaena australis*)	New Zealand	Marine mammal	Y		
Wrege et al., 2017	Discussion of the utility of methods for elephant conservation	Central Africa	Terrestrial mammal	Y		

studies have paired camera traps and acoustic monitoring, several research groups have begun to use these techniques together at large scales (e.g., http://bioacoustic.abmi.ca, http://www.soundandlightecologyteam.colostate.edu).

3. Future application of pairing camera traps and acoustic monitoring

3.1. Human disturbance

Pairing camera traps and acoustic recorders can capture complementary extents and types of human disturbance. In particular, paired acoustic and camera data can collect data on the type and degree of illegal activities, hunting, anthropogenic noise, and general human presence in real time (Barber et al., 2010; Hossain et al., 2016; Miller et al., 2017). Photographs can distinguish detailed information about human disturbance, such as the identification of specific activities or wildlife crime perpetrators, enhancing detection of illegal activity where patrolling resources are scarce (Hossain et al., 2016). However, detection rates depend on camera placement along high-traffic routes and detections are limited to the camera's field of view. Thus, the addition of acoustic recorders can widen the radius of human activity surveillance, capturing sound which, depending on terrain, can propagate for long distances (e.g. the presence and direction of gun fire from >1 km; Astaras et al., 2017). It is well documented that noise pollution changes the distribution of wildlife (Shannon et al., 2016); however, the mechanisms behind avoidance behavior remain unclear (Francis and Barber, 2013). Camera traps and acoustic recorders could address this uncertainty by pairing behavioral observations with real-time measurements of sound pressure levels.

By capturing various types of stressors over a landscape, which may additionally include gradients of habitat disturbance, camera traps paired with acoustic monitoring can allow investigation of the effects of multiple interacting threats on wildlife (Fig. 1). For example, rapidly expanding human development, such as unconventional energy development, results in novel disturbance patterns, with a direct physical footprint and broad impacts from noise, light, and human activity (Souther et al., 2014). Pairing camera traps and acoustic recorders could examine the synergistic or additive impacts of infrastructure and associated human activity on wildlife (Darling and Côté, 2008).

3.2. Biotic interactions

Coupled acoustic and camera monitoring can enhance the number of species and area surveyed given that each method can sample different taxa. Camera traps sample medium to large terrestrial species (e.g., mammalian carnivores and herbivores), but often do not detect smaller species (e.g., smaller vertebrates and invertebrates) or avian and arboreal species (e.g., birds and primates). Acoustic recordings capture sound-producing species (e.g., birds, insects, vocalizing mammals), but do not reliably detect non-vocal or quiet animals (e.g., some herbivores and carnivores; KRC unpublished data). In this way, coupled monitoring can provide novel insight into interactions across multiple trophic levels and guilds, allowing more insight into community structure (Fig. 1). For example, camera traps could measure the abundance and habitat use of wide-ranging species, while acoustic recorders could assess their potential as umbrella species by quantifying the richness of the vocalizing community (Fleishman et al., 2000). Additionally, by capturing variation in densities of predators, and mammalian, avian, and arthropod prey across altered landscapes, camera traps and acoustic recorders could give insight into the effects of human disturbance on interspecific interactions, including predator-prey and competitive relationships. Finally, assessing biotic interactions at macroecological scales could help investigate the role of local-scale community processes in regulating large-scale diversity (Brooker Rob et al., 2009).

3.3. Animal behavior at multiple scales

Human disturbance can result in more subtle changes to animal behavior, which may provide an early warning of population decline or changes in habitat use (Berger-Tal et al., 2011). For example, some carnivores are less active during the day in sites with development compared to undeveloped sites (Gaynor et al., 2018). Moreover, many animals will shift the timing (Dominoni et al., 2016), frequency (Lampe et al., 2012), rate (Proppe and Finch, 2017), and sound levels (Brumm, 2004) of their vocalizations in the presence of anthropogenic noise with unknown ecological consequences. The large temporal and spatial extent of both camera traps and acoustic recorders offer insight into how these alterations in activity patterns and vocalizations may translate to significant changes in habitat use and distribution. Moreover, each technique provides a complementary but unique level of inference, where acoustic recorders have a broader detection distance while cameras capture detailed visual information about individuals and behaviors in the immediate vicinity of the camera. These paired resolutions of inference can provide synergistic information when analyses are combined. Finally, each method provides a permanent record of a survey period, allowing repeated listening or viewing by multiple observers to increase accuracy and facilitate multiple types of behavioral analyses (Haselmayer and Quinn, 2000).

Using both techniques concurrently also can improve estimates of detection probability associated with each method. Species are not detected with certainty using either camera traps or acoustic recorders, and especially for rare and elusive species, occupancy can be underestimated (Diggins et al., 2016). The presence of false negative data (failure to detect a species when it is present) can lead to skewed estimates of distribution, population status, or trends (Gu and Swihart, 2004). By pairing camera traps and acoustic recorders, one method can capture the other's false negatives, offering a means to estimate detection probability non-invasively. Analytical tools to integrate these data using multi-scale occupancy estimation exist, but are generally underused (Nichols et al., 2008).

4. Remaining challenges and research opportunities

Despite the major advancements in camera trapping and acoustic recording technology, challenges remain. Firstly, commercially available acoustic recording units and camera traps can be costly (typically ranging from approximately 200-1000 USD), potentially precluding their large-scale implementation outside of well-funded research groups. However, more affordable acoustic devices (Beason et al., 2018; Hill et al., 2018) and camera traps (Rico-Guevara and Mickley, 2017) have been developed and are generally open-source or readily available. Secondly, camera and acoustic data must be downloaded and sorted, which can require considerable time and effort. Wireless networks to transmit data are under development, with the potential to increase efficiency (e.g., decreasing the number of servicing trips) and potential applications (e.g., anti-poaching) of camera trapping and acoustic recording (Kays et al., 2009; McKown et al., 2012; Aravinda et al., 2016; Kamminga et al., 2018). Further, software programs are available to facilitate sorting of images (Young et al., 2018) and acoustic data (National Park Service, 2013; SonoBat, 2016). Thirdly, extracting biological information from the enormous amounts of data resulting from either method can be time consuming and quantitative analysis is challenging. For camera traps, citizen science initiatives have been developed to help identify the contents of photographs (e.g., Zooniverse, Snapshot Serengeti) and machine learning is being developed to classify species captured in photographs (Tabak et al., 2018). For acoustic recordings, automated methods have been developed, including algorithms to identify species vocalizations (Potamitis, 2014), visualization of long duration recordings (Towsey et al., 2014), and acoustic indices that reflect bioacoustic activity in recordings (Buxton et al., 2018). Occupancy modeling is regularly used to account for the detectability using camera traps and acoustic recorders (MacKenzie et al., 2006; Burton et al., 2015), random encounter models have led to better estimates of animal density (Lucas et al., 2015), and hierarchical models can scale-up estimates of species richness (Tobler et al., 2015).

Finally, arguably the principle challenge facing paired camera traps and acoustic recorders is the computational and logistical burden of processing and storing data sets. One of the fundamental strengths of camera trap and acoustic data is their ability to deliver valuable information beyond their original collection purpose and to be integrated at continental or global scales. However, this requires enormous volumes of data to be managed, archived, and openly accessible (e.g., hundreds of terabytes of acoustic data; ABMI, 2016; Mennitt and Fristrup, 2016). Public repositories of data at this scale will require a solid funding base and trans-organizational collaboration (Michener, 2015; Specht et al., 2015). Although there are now mechanisms in place to aid in data sharing (www.esa.org/esa/science/data-sharing/resources-and-tools/), there are many challenges and opportunities facing the storage and maintenance of big ecological data (Hampton et al., 2013; Schimel and Keller, 2015), with much to be learned from industry's data management platforms (Tien, 2013) and museum procurement approaches.

Notably, camera traps and acoustic recorders share similar challenges and opportunities. Thus, we propose that by developing these techniques simultaneously, rather than independently, innovations can more efficiently be applied to both techniques. Furthermore, the simultaneous development of camera traps and acoustic recorders would result in even greater compatibility between the methods, further improving our ability to effectively use big data to monitor biodiversity globally.

5. Conclusion

Delivering technology that can provide robust indicators of biodiversity from regional to global scales is key to examining anthropogenic threats on ecological systems. Integrating two widely used monitoring techniques, camera traps and acoustic recorders, offers the opportunity to collect spatially and temporally explicit animal and human activity data across large spatial extents. This allows the investigation of biotic interactions (Wisz et al., 2013), community composition, population dynamics, and behavioral processes across gradients of anthropogenic disturbance and activity. Combining and refining these technologies will continue to revolutionize ecological and behavioral sciences.

Acknowledgements

We thank M. McKenna, and other National Park Service staff for helpful discussion. This work was supported by the National Park Service Natural Sounds and Night Skies Division and ExxonMobil Production/XTO Energy.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gecco.2018.e00493.

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