**Abstract**

1. Camera traps are one of the most common tools in wildlife and conservation biology. Sampling can document and measure animal presence and activity. Captures can be used to estimate population parameters such as presence, abundance, habitat suitability, and resident species richness of specific populations. Effective camera trapping is relevant to conservation for many reasons. For instance, they can be used to inform pre and post-restoration efforts, monitor the use of artificial structures by species and assess behaviours like predator-prey interactions. This sampling approach can aid in assessing diversity change, habitat change, pre/post restoration efforts, artificial structure effects, species presence, and animal behaviour.
2. We reviewed the literature to collect data and estimate incidence effect size measures for both vertebrate abundance and vertebrate richness to examine the relative efficacy of deploying more camera traps for a given period in different ecosystems. A total of 292 full-text articles were returned from the Web of Science using the search terms camera\* and trap\* and richness\* or diversity\*, and rarefaction\* curve\*. Full-text reviews of each sampling effort returned 149 studies that reported animal abundance and species richness that we used in this meta-analysis.
3. Increasing sampling effort through an increased number of cameras significantly increased net positive abundance detection rates in grasslands and mixed ecosystems. Net richness detection rates in mixed, tropical, deciduous, and grassland ecosystems similarly increased with the number of cameras deployed. The total number of days however was not a significant predictor of abundance or richness rates detected in any ecosystem. We also estimated the Minimum Trapping Effort (MTE) to find the optimal number of days of trapping for both abundance and richness per camera within a site or a region. These findings suggest that deploying relatively more cameras for relatively fewer days provides the most effective estimates of vertebrate abundance and richness for a region.

**Keywords**

Conservation, Minimum Trapping Effort (MTE), population, sampling effort, vertebrates.

**Introduction**

Monitoring and measuring the number of animals and diversity of animal communities in terrestrial ecosystems comprises an important set of methods in ecology and evolution. Camera traps are frequently a primary tool to survey wildlife and their interactions with the surrounding environment. These survey devices normally record animal presence via a triggered passive, infrared motion sensor (Rowcliffe et al., 2011). They are one of the most popular survey tools in current wildlife research, particularly in the domain of terrestrial vertebrate biology (Meek et al., 2014). Cameras can record activity patterns and be used to infer occupancy, abundance, and species diversity (Kelly, 2008; O’Connell et al., 2011). Camera traps have also been used in studies to examine behaviour (Rowcliffe et al., 2014), habitat use (Rovero et al., 2014), detection of rare species in a community (Thomas et al., 2020), estimation of population size and species richness (Whytock et al., 2021), and occupation of human-built structures (O’Connell et al., 2011). Thus, camera trap data can be used to quantify many ecological parameters and help advance theories such as niche partitioning, habitat use, as well as various behavioural models (Frey et al., 2017; Smith et al., 2020). They are also a fundamental species monitoring tool in higher conservation value ecosystems such as the Serengeti (Swanson et al., 2015) and the Amazon Basin (Trolle, 2003). These data can then be used to evaluate the efficacy of survey designs (Kays et al., 2020) to support management.

Various factors can influence the number of species detected by camera traps, as well as the trapping rate (ratio of photographs of particular individuals of a species to camera trapping duration) (Rovero & Marshall, 2009). The camera model, placement and orientation, temperature differentials, and species' behavioural responses are some of the factors that impact the collected data (Meek et al., 2015). Thus, study design decisions include camera model, number of cameras, duration, and placement within a system. The factors above can be summarized as trapping effort and trapping design, which can influence abundance and diversity estimates (Wegge et al., 2004; Yasuda, 2004). Trapping rate is a useful index for abundance and diversity estimates (Rovero and Marshall 2009; Rowcliffe et al., 2008; Silveira et al., 2003). Minimum trapping effort (MTE) is another important factor for population estimates (Si et al., 2014). MTE refers to the number of camera trap days required to record species of interest in an area and varies extensively across studies (Si et al., 2014). Sampling design decisions can be directly related to factors such as funding that can affect detection probabilities and impact the strength of population estimates (Foster & Harmsen, 2012). The interplay amongst these factors provides us with an excellent opportunity to explore the relationship between trapping duration, number of cameras, and richness and abundance estimates across the literature, worldwide.

Globally, many species are threatened by anthropogenic challenges such as climate change, pollution, habitat loss, and hunting. The capacity of camera traps shows that this simple technology if effectively deployed can be used in directing conservation actions including when and where species are doing well or declining and what factors are different between these stations (Wich & Piel, 2021). In addition, it can show us to the extent that species diversity is changing (Rich et al., 2017). Camera trapping in different habitats can be used to identify species' habitat preferences, niche models, and range models (Wich & Piel, 2021) such that biologists can inform assessments of the effectiveness of different potential management strategies. For example, the distribution patterns of secretive mammals in Tanzania were documented using camera traps for the distribution of the bushy-tailed mongoose (*Bdeogale crassicauda*) (Pettorelli et al., 2010). This species was detected at higher rates in national park areas than in-game reserves. Spatial comparison using camera traps can also serve as a threat assessment (de Oliveira et al., 2020). In a private reserve in Africa, camera trap imagery demonstrated that trophy hunting of leopards contributed to the fall of the population size below carrying capacity (Chapman & Balme, 2010). The implementation of cameras for conservation is thus varied and there are many other implications and uses (Table 2). As such, camera trapping not only allows for the monitoring of wildlife, but also enables the evaluation of conservation actions.

The TEAM project is an excellent example of a partnership between various organizations that does standardized camera trapping of 17 protected areas worldwide (Fegraus et al., 2011). In one of their studies, this partnership examined the protection of threatened mammal populations by comparing and contrasting poorly-protected forest sites and reserve sites in Tanzania. They found a reduction in species richness, community structure, and species-specific occupancy in unprotected sites (Oberosler et al., 2020). This partnership has also shown that a ban on threats, such as firewood, can positively affect animal communities. Wildlife biologists commonly rely on camera trap studies for conservation. Synthesis of the effectiveness of experimental deployments of camera traps thus falls at the heart of informing conservation.

We used a meta-analysis to look at the total number of cameras and the total number of days to assess the relative impact of sampling effort design decisions. Previous methods such as rarefaction curves and extrapolations developed by Chao et al., (2014) do provide us with the means to quantify the relationship between sampling effort and estimates of richness and abundance; however, herein we developed two incidence effect size measures used in other fields (Ilies et al., 2003; Li et al., 2018) to evaluate the relationship between abundance and richness by sampling effort when you do not have diversity or population estimate data from the field. We hypothesized that sampling size can be used to inform us of the optimal way of allocation sampling effort. Furthermore, we estimated the inflection points (Goshu, 2013) for both net abundance and net richness indices to obtain the MTE required for abundance per camera and richness per camera. The importance of these critical design decisions was also assessed for different ecosystems. Given that camera traps are increasingly used in ecology and evolution (Tabak et al., 2019), this synthesis provides an insight into the ‘sweet spot’ for potential optimal sampling before one begins a field study in any ecosystem. The capacity for this method to provide meaningful and sufficient animal data will better inform conservation efforts and fundamental theory.

**Methods**

***Literature review***

We reviewed the literature to obtain data for a measure of richness or diversity, the number of captures (abundance), and the duration of camera trapping (i.e. days). We conducted a systematic review using the terms camera trap\* and richness\*, or diversity\*, and camera\* trap\* and rarefaction\* curve\* in ISI Web of Science (WoS) (*Web of Science.*, 2021) as two searches. These searches were done in the latter quarter of 2021. Additionally, we conducted supplemental searches in book chapters and Google Scholar to validate the publication coverage of WoS. This process resulted in a total of 557 publications, once duplicates were removed, spanning the years 2001-2021. A PRISMA diagram illustrates the exclusion and review process (Moher et al., 2009) (Supplementary Appendix, Figure A). We used best practices to ensure that workflow and synthesis were reproducible and transparent (Bayliss & Beyer, 2015). We screened the abstracts and excluded papers based on relevance, whether they were a review, opinion, or idea paper, focused on aquatic ecosystems, were not written in English (or the English text version was unavailable), were qualitative, did not examine vertebrate species, and if they focused on one species or a group of animals (such as wild cats) and ignored other observed animals. A total of 292 full-text articles were reviewed for a measure of richness or diversity, the number of captures, and/or duration of camera trapping (i.e. days) of which 149 full-text articles had viable data and were included in the final analysis. Data were extracted from article text or tables. Variables such as the location of the study, number of cameras, sites, and ecosystem were also recorded.

***Meta-Analyses***

All meta-statistical analyses were performed in R version 4.2.2 (R Development Core Team, 2023). Effect sizes were calculated using the number of species and the number of animals (captures) using the incidence rates in the package *metafor* version 3.0-2 (Viechtbauer, 2010). The incidence rates for the effect size measure were calculated by dividing the number of animals or the number of species against the total number of cameras by the total number of study days (Higgins et al., 2021). These indices are defined as net abundance and net richness detection rates. Random-effects models (*rma)* were used to model estimated indices and their standard errors with ‘Ecosystem’ serving as moderator. This was done to model the effects of deploying more cameras on net abundance and net richness and see estimated significance. ‘Ecosystems’ were extracted from the studies and later narrowed down to six main ecosystems, including coniferous, deciduous, tropical, grassland, mixed, and desert. Mixed ecosystem referred to any ecosystem that was a combination of two or more ecosystems listed in the analyses. Weighted regression models were applied to analyze estimated values for abundance per camera and richness per number of cameras over the total number of days to correct for heteroscedasticity (Kutner et al., 2005). In this procedure, more weight is given to observations with smaller variances to provide more reliable information about the regression function than those with large variances (Kutner et al., 2005). Heterogeneity in all models was examined to ensure that variance was not unduly inflated from grouping similar measures into the random-effect models (Langan et al., 2019). Heterogeneity was tested by examining Cochran’s Q statistic (Bowden et al., 2011). Publication bias was tested using Egger’s regression test (Egger et al., 1997).

**Results**

A total of 149 articles were included in the meta-analysis comprising 3428 unique sites. The supporting R scripts are published on Zenodo (Ghazian and Lortie, 2021), and data are published on Knowledge Network for Biocomplexity (KNB) (Ghazian & Lortie, 2021). The most common ecosystems for the studies were tropical (38) and deciduous forest (25 studies). Observed vertebrates were small and large mammals, birds, and reptiles. The number of study days varied between 230-48350 days.

Net abundance detection rate estimates resulted in an asymmetric funnel plot, suggesting systematic differences between the studies (Supplementary Appendix, Figure B, heterogeneity p<0.0001). Ecosystem was a significant moderator in the model for net abundance detection rates (F = 4.8830, p = 0.0003, *df* = 6). The effect of deploying more cameras was significantly positive in grassland and mixed ecosystems (Figure 1 and Table 1). Systematic differences between studies were also shown in funnel plots of net richness detection rates (Supplementary Appendix, Figure C, heterogeneity p<0.0001). Ecosystem was a significant moderator in the model (F = 14.79, p<0.0001, *df* = 6). Furthermore, the net effect of deploying more cameras was positive in mixed, tropical, deciduous, and grassland ecosystems (Figure 1, Table 1). Abundance per camera regressed against the total number of days showed significant heterogeneity between groups (Figure 2, R2 = 0.0%, heterogeneity p<0.0001). This was also shown for richness regressed against the number of days (Figure 2, R2 = 0.73%, heterogeneity p<0.0001). The MTE for abundance per camera was 3236 days and 855 days for richness per camera was calculated based on inflection when the rate was convex (Goshu, 2013). There was no effect of increasing the duration of the study (i.e. total number of days) on abundance per camera deployed (F = 0.0037, p<0.952, *df* = 1), or richness per camera (F = 0.3698, p<0.545, *df* = 1).

**Discussion**

The conservation and restoration of the world's ecosystems ultimately depend on the ability to identify wildlife and estimate biodiversity effectively. The hypothesis that sampling size can be used to inform us of the optimal way of allocating sampling effort was supported here. Deploying more camera traps, but not necessarily for more days, is likely the most effective ecological tool to estimate abundance in grassland and mixed ecosystems, as well as local species richness in all but coniferous forests and deserts. ‘Ecosystem’ was relevant and some systems require additional study. The estimated MTE does not necessarily mean per study but does suggest that within a site or region, it is valuable to consider deployment differently. Our study showed that deploying more cameras versus longer for the same sample is better for estimating abundance in grassland and mixed ecosystems and richness in all ecosystems, except for deserts and coniferous forests. Thus, it is important to frame quantitative expectations based on the returns published in similar studies or summarized in syntheses like this study.

Camera traps effectively estimate population parameters in many different ecosystems worldwide. Herein, we examined the net abundance detection rate and net richness detection rate. Examining both these indices, we found evidence that richness and abundance were influenced by the number of cameras deployed at a site or region. The primary finding of this synthesis is that success in detecting species in a given system was highly dependent on the number of cameras. This is aligned with the findings of Ferreras et al. (2017) which suggests that for effective detection, it is more efficient to deploy more camera traps for a shorter duration rather than to deploy fewer camera traps for a longer period. Although the number of cameras is important, there are at least two other design decisions associated with camera deployment: placement and habitat type. The number of cameras is not independent of camera deployment because more cameras can increase the likelihood of overlap and sampling more environmental heterogeneity. To increase sampling effort through more cameras, a systematic trap placement design or a design suited to that particular habitat is essential if the primary goal of the survey is population parameter estimation, such as richness (O’Brien, 2008). To limit the chance of missing species, camera traps should not be too close together and maximize the total area covered (O’Connell et al., 2011). If multiple cameras are placed in one site, placement should be systematic and cameras should have different fields of view to maximize the detection of animals (Pease et al., 2016). Random and systematic (grid) camera setups can both result in similar estimates of species richness and group size, but differ in estimates of abundance and activity pattern (Tanwar et al., 2021). Sampling effort is also a critical design topic in all of ecology and evolution (Albert et al., 2010; Hamel et al., 2013), particularly in field studies. In this study, we found that increasing the number of trapping days is not a significant predictor of increased capacity for cameras to detect more animals neither in abundance, nor diversity. This is directly related to Minimum Trapping Effort (MTE) (Si et al., 2014) because MTE is the number of camera trap days required to detect a terrestrial species of interest in an area record. The interdependence of camera trap placement and the number of cameras is not a hypothesis explicitly tested in this meta-analysis. However, it is integral in maximizing the potential of camera traps for wildlife monitoring. Understanding how many cameras are needed for how long, and how far apart they need to be placed relative to the particular ecosystem of study will ensure more precise data are obtained for species diversity and habitat change, behaviour, and use of artificial strucutures, which is critical for conservation.

It was striking that increasing the number of cameras significantly increased the net abundance detection rate in only grasslands and mixed ecosystems. One reason that animal abundance was higher in grasslands, as opposed to other arid lands, may be due to the abundance of prey, such as mice or birds, alongside the natural grass and vegetation. This in turn attracts more mid-size or larger mammals that feed on these small animals (Silveira et al., 2005) that can be easily detected by cameras. Vegetation can augment the abundance of prey and predators, hence increasing the total observed animal abundance in the area (Barbosa & Castellanos, 2005). Furthermore, mixed systems support relatively higher habitat diversity because they are comprised of many different types of plant species (Felton et al., 2010). It is likely that this heterogeneity supports a greater number of animals because of resources and habitats (MacArthur & MacArthur, 1961). Net richness detection rate did not significantly increase with the number of cameras. Arid and semi-arid systems are globally threatened by increased rates of anthropogenic changes, such as climate and land-use changes (Mahmoud and Gan 2018), and species in these regions face extensive ecological shifts (Barrows 2011; Bachelet et al. 2016). Hence, the reason why species diversity may not increase with more camera trap sampling may be due to the fact diversity in animal communities is declining in drylands (Maestre et al., 2016). Landscape-level differences influence animal assemblage in different ecosystems and offer us valuable insight into the utility of camera traps in different regions.

**Implications for Optimal Camera Trapping**

This synthesis provides both a critical insight into experimental design considerations associated with sampling efforts and the relative efficacy of camera traps as a tool in monitoring changes in wildlife populations in different ecosystems. Across the same sample size, deploying more camera traps over a shorter duration, with appropriate placement, is the most effective strategy as estimated from the relevant published scientific literature to date – across studies. This trend is likely relevant within studies at a specific site or region. Increasing camera traps is certainly a more effective sampling strategy, in general, to increase relative sampling effort spatially. Purchasing more cameras is a more efficient strategy for conservation biology and stakeholders, including land owners and nature conservancies in the area. We understand that camera trapping generally requires a large sum of initial funding, but this funding is offset by the low efforts required for camera trapping fieldwork (Lamelas-López & Salgado, 2021). Cameras are more affordable than intensive sampling via direct observational survey because over time hiring people to do fieldwork takes more funding than the initial cost of camera traps. Results of population estimates from camera trapping sampling compare favourbly with those of traditional live trapping techniques, and funds saved from not doing live trapping can be invested in purchasing camera traps (De Bondi et al., 2010). Of course, the recommendation is not to replace researchers with cameras because nonetheless photos captured by cameras still need to be processed; however, despite greater initial costs, camera traps are a more reliable monitoring tool to identify species since species identification in live surveys is highly-dependent on the person’s confidence of species identification (Roberts, 2011). We do suggest however that with the increase in the number of cameras, the setting and programming be as simple as possible to allow workers with varying degree of field experience to effectively conduct trapping without errors (Rovero et al., 2013). Furthermore, we understand that seasonality can impact species detection because of migration and hibernation (Kays et al., 2020; Tape & Gustine, 2014); thus, sampling may need to be done in all seasons, and for long-term monitoring, repeated visits/continuous sampling may be necessary. Our results direct us towards the necessity to better examine survey efforts, experimental design, and camera trap placement to increase detection probabilities of wildlife to ensure good data for management to make better-informed restoration and conservation decisions.

**Acknowledgments**

This research was made possible through a Natural Sciences and Engineering Research Council of Canada (NSERC) grant awarded to CJL. NG and CJL declare no conflict of interest.

**Acknowledgment of Country**

We acknowledge the First Nation communities that are the Traditional Custodians of the land on which much of this camera trapping research was done and pay our respects to their Elders past and present.

**Author**’**s contributions**

NG and CJL designed the study and methodologies; NG wrote the manuscript; NG and CJL analyzed the data; CJL thoroughly edited the manuscript and contributed critically.

**Work Cited**

Albert, C. H., Yoccoz, N. G., Edwards, T. C., Graham, C. H., Zimmermann, N. E., & Thuiller, W. (2010). Sampling in ecology and evolution—Bridging the gap between theory and practice. *Ecography*, *33*(6), 1028–1037. https://doi.org/10.1111/j.1600-0587.2010.06421.x

Barbosa, P., & Castellanos, I. (Eds.). (2005). *Ecology of predator-prey interactions*. Oxford University Press.

Bayliss, H. R., & Beyer, F. R. (2015). Information retrieval for ecological syntheses: Information retrieval for ecological syntheses. *Research Synthesis Methods*, *6*(2), 136–148. https://doi.org/10.1002/jrsm.1120

Bowden, J., Tierney, J. F., Copas, A. J., & Burdett, S. (2011). Quantifying, displaying and accounting for heterogeneity in the meta-analysis of RCTs using standard and generalised Qstatistics. *BMC Medical Research Methodology*, *11*(1), 41. https://doi.org/10.1186/1471-2288-11-41

Chao, A., Gotelli, N. J., Hsieh, T. C., Sander, E. L., Ma, K. H., Colwell, R. K., & Ellison, A. M. (2014). Rarefaction and extrapolation with Hill numbers: A framework for sampling and estimation in species diversity studies. *Ecological Monographs*, *84*(1), 45–67. https://doi.org/10.1890/13-0133.1

Chapman, S., & Balme, G. (2010). An Estimate of Leopard Population Density in a Private Reserve in KwaZulu-Natal, South Africa, using Camera—Traps and Capture-Recapture Models. *South African Journal of Wildlife Research*, *40*(2), 114–120. https://doi.org/10.3957/056.040.0202

De Bondi, N., White, J. G., Stevens, M., & Cooke, R. (2010). A comparison of the effectiveness of camera trapping and live trapping for sampling terrestrial small-mammal communities. *Wildlife Research*, *37*(6), 456. https://doi.org/10.1071/WR10046

de Oliveira, T. G., Lima, B. C., Fox-Rosales, L., Pereira, R. S., Pontes-Araújo, E., & de Sousa, A. L. (2020). A refined population and conservation assessment of the elusive and endangered northern tiger cat (Leopardus tigrinus) in its key worldwide conservation area in Brazil. *Global Ecology and Conservation*, *22*, e00927. https://doi.org/10.1016/j.gecco.2020.e00927

Egger, M., Smith, G. D., Schneider, M., & Minder, C. (1997). Bias in meta-analysis detected by a simple, graphical test. *BMJ*, *315*(7109), 629–634. https://doi.org/10.1136/bmj.315.7109.629

Fegraus, E. H., Lin, K., Ahumada, J. A., Baru, C., Chandra, S., & Youn, C. (2011). Data acquisition and management software for camera trap data: A case study from the TEAM Network. *Ecological Informatics*, *6*(6), 345–353. https://doi.org/10.1016/j.ecoinf.2011.06.003

Felton, A., Lindbladh, M., Brunet, J., & Fritz, Ö. (2010). Replacing coniferous monocultures with mixed-species production stands: An assessment of the potential benefits for forest biodiversity in northern Europe. *Forest Ecology and Management*, *260*(6), 939–947. https://doi.org/10.1016/j.foreco.2010.06.011

Ferreras, P., Díaz-Ruiz, F., Alves, P. C., & Monterroso, P. (2017). Optimizing camera-trapping protocols for characterizing mesocarnivore communities in south-western Europe. *Journal of Zoology*, *301*(1), 23–31. https://doi.org/10.1111/jzo.12386

Foster, R. J., & Harmsen, B. J. (2012). A critique of density estimation from camera-trap data: Density Estimation From Camera-Trap Data. *The Journal of Wildlife Management*, *76*(2), 224–236. https://doi.org/10.1002/jwmg.275

Frey, S., Fisher, J. T., Burton, A. C., & Volpe, J. P. (2017). Investigating animal activity patterns and temporal niche partitioning using camera-trap data: Challenges and opportunities. *Remote Sensing in Ecology and Conservation*, *3*(3), 123–132. https://doi.org/10.1002/rse2.60

Ghazian, N., & Lortie, C. (2021). *A global synthesis and meta-analysis of net capture abundance and richness detection rates as an index of sampling effort, 2021.* [Text/xml]. KNB Data Repository. https://doi.org/10.5063/3J3BC3

Goshu, A. T. (2013). Derivation of Inflection Points of Nonlinear Regression Curves—Implications to Statistics. *American Journal of Theoretical and Applied Statistics*, *2*(6), 268. https://doi.org/10.11648/j.ajtas.20130206.25

Hamel, S., Killengreen, S. T., Henden, J.-A., Eide, N. E., Roed-Eriksen, L., Ims, R. A., & Yoccoz, N. G. (2013). Towards good practice guidance in using camera-traps in ecology: Influence of sampling design on validity of ecological inferences. *Methods in Ecology and Evolution*, *4*(2), 105–113. https://doi.org/10.1111/j.2041-210x.2012.00262.x

Ilies, R., Hauserman, N., Schwochau, S., & Stibal, J. (2003). REPORTED INCIDENCE RATES OF WORK-RELATED SEXUAL HARASSMENT IN THE UNITED STATES: USING META-ANALYSIS TO EXPLAIN REPORTED RATE DISPARITIES. *Personnel Psychology*, *56*(3), 607–631. https://doi.org/10.1111/j.1744-6570.2003.tb00752.x

Kays, R., Arbogast, B. S., Baker‐Whatton, M., Beirne, C., Boone, H. M., Bowler, M., Burneo, S. F., Cove, M. V., Ding, P., Espinosa, S., Gonçalves, A. L. S., Hansen, C. P., Jansen, P. A., Kolowski, J. M., Knowles, T. W., Lima, M. G. M., Millspaugh, J., McShea, W. J., Pacifici, K., … Spironello, W. R. (2020). An empirical evaluation of camera trap study design: How many, how long and when? *Methods in Ecology and Evolution*, *11*(6), 700–713. https://doi.org/10.1111/2041-210X.13370

Kelly, M. J. (2008). Design, evaluate, refine: Camera trap studies for elusive species. *Animal Conservation*, *11*(3), 182–184. https://doi.org/10.1111/j.1469-1795.2008.00179.x

Kutner, M. H., Nachtsheim, C., Neter, J., & Li, W. (2005). *Applied linear statistical models* (5th edition). McGraw-Hill Irwin.

Lamelas-López, L., & Salgado, I. (2021). Applying camera traps to detect and monitor introduced mammals on oceanic islands. *Oryx*, *55*(2), 181–188. https://doi.org/10.1017/S0030605319001364

Langan, D., Higgins, J. P. T., Jackson, D., Bowden, J., Veroniki, A. A., Kontopantelis, E., Viechtbauer, W., & Simmonds, M. (2019). A comparison of heterogeneity variance estimators in simulated random‐effects meta‐analyses. *Research Synthesis Methods*, *10*(1), 83–98. https://doi.org/10.1002/jrsm.1316

Li, X., Bleisch, W. V., & Jiang, X. (2018). Using large spatial scale camera trap data and hierarchical occupancy models to evaluate species richness and occupancy of rare and elusive wildlife communities in southwest China. *Diversity and Distributions*, *24*(11), 1560–1572. https://doi.org/10.1111/ddi.12792

MacArthur, R. H., & MacArthur, J. W. (1961). On Bird Species Diversity. *Ecology*, *42*(3), 594–598. https://doi.org/10.2307/1932254

Maestre, F. T., Eldridge, D. J., Soliveres, S., Kéfi, S., Delgado-Baquerizo, M., Bowker, M. A., García-Palacios, P., Gaitán, J., Gallardo, A., Lázaro, R., & Berdugo, M. (2016). Structure and Functioning of Dryland Ecosystems in a Changing World. *Annual Review of Ecology, Evolution, and Systematics*, *47*(1), 215–237. https://doi.org/10.1146/annurev-ecolsys-121415-032311

Marcus Rowcliffe, J., Carbone, C., Jansen, P. A., Kays, R., & Kranstauber, B. (2011). Quantifying the sensitivity of camera traps: An adapted distance sampling approach: *Quantifying camera trap sensitivity*. *Methods in Ecology and Evolution*, *2*(5), 464–476. https://doi.org/10.1111/j.2041-210X.2011.00094.x

Meek, P. D., Ballard, G.-A., & Fleming, P. J. S. (2015). The pitfalls of wildlife camera trapping as a survey tool in Australia. *Australian Mammalogy*, *37*(1), 13. https://doi.org/10.1071/AM14023

Meek, P., Fleming, P. J. S., Ballard, G., Banks, P., Claridge, A. W., Sanderson, J., Swann, D. E., Australasian Wildlife Management Society, & Royal Zoological Society of New South Wales (Eds.). (2014). *Camera trapping: Wildlife management and research*.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., & The PRISMA Group. (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *PLoS Medicine*, *6*(7), e1000097. https://doi.org/10.1371/journal.pmed.1000097

Oberosler, V., Tenan, S., Zipkin, E. F., & Rovero, F. (2020). When parks work: Effect of anthropogenic disturbance on occupancy of tropical forest mammals. *Ecology and Evolution*, *10*(9), 3881–3894. https://doi.org/10.1002/ece3.6048

O’Brien, T. G. (2008). On the use of automated cameras to estimate species richness for large- and medium-sized rainforest mammals. *Animal Conservation*, *11*(3), 179–181. https://doi.org/10.1111/j.1469-1795.2008.00178.x

O’Connell, A. F., Nichols, J. D., & Karanth, K. U. (Eds.). (2011). *Camera traps in animal ecology: Methods and analyses / Allan F. O’Connell, James D. Nichols, K. Ullas Karanth, editors*. Springer.

Pease, B. S., Nielsen, C. K., & Holzmueller, E. J. (2016). Single-Camera Trap Survey Designs Miss Detections: Impacts on Estimates of Occupancy and Community Metrics. *PLOS ONE*, *11*(11), e0166689. https://doi.org/10.1371/journal.pone.0166689

Pettorelli, N., Lobora, A. L., Msuha, M. J., Foley, C., & Durant, S. M. (2010). Carnivore biodiversity in Tanzania: Revealing the distribution patterns of secretive mammals using camera traps. *Animal Conservation*, *13*(2), 131–139. https://doi.org/10.1111/j.1469-1795.2009.00309.x

PT Higgins, J., Li, T., & Deeks, J. J. (2021). Choosing effect measures and computing estimates of effect. *Cochrane Training*. https://training.cochrane.org/handbook/current/chapter-06#section-6-1

R Development Core Team. (2022). *R* (4.2.0).

Rich, L. N., Davis, C. L., Farris, Z. J., Miller, D. A. W., Tucker, J. M., Hamel, S., Farhadinia, M. S., Steenweg, R., Di Bitetti, M. S., Thapa, K., Kane, M. D., Sunarto, S., Robinson, N. P., Paviolo, A., Cruz, P., Martins, Q., Gholikhani, N., Taktehrani, A., Whittington, J., … Kelly, M. J. (2017). Assessing global patterns in mammalian carnivore occupancy and richness by integrating local camera trap surveys: RICH et al. *Global Ecology and Biogeography*, *26*(8), 918–929. https://doi.org/10.1111/geb.12600

Roberts, N. J. (2011). Investigation into survey techniques of large mammals: Surveyor competence and camera-trapping vs. transect-sampling. *Bioscience Horizons: The International Journal of Student Research*, *4*(1), 40–49. https://doi.org/10.1093/biohorizons/hzr006

Rovero, F., & Marshall, A. R. (2009). Camera trapping photographic rate as an index of density in forest ungulates. *Journal of Applied Ecology*, *46*(5), 1011–1017. https://doi.org/10.1111/j.1365-2664.2009.01705.x

Rovero, F., Zimmermann, F., Berzi, D., & Meek, P. (2013). “Which camera trap type and how many do I need?” A review of camera features and study designs for a range of wildlife research applications. *Hystrix, the Italian Journal of Mammalogy*, *24*(2). https://doi.org/10.4404/hystrix-24.2-8789

Rowcliffe, J. M., Kays, R., Kranstauber, B., Carbone, C., & Jansen, P. A. (2014). Quantifying levels of animal activity using camera trap data. *Methods in Ecology and Evolution*, *5*(11), 1170–1179. https://doi.org/10.1111/2041-210X.12278

Si, X., Kays, R., & Ding, P. (2014). How long is enough to detect terrestrial animals? Estimating the minimum trapping effort on camera traps. *PeerJ*, *2*, e374. https://doi.org/10.7717/peerj.374

Silveira, L., Jácomo, A. T. A., & Diniz-Filho, J. A. F. (2003). Camera trap, line transect census and track surveys: A comparative evaluation. *Biological Conservation*, *114*(3), 351–355. https://doi.org/10.1016/S0006-3207(03)00063-6

Silveira, L., Jácomo, A. T. A., & Malzoni Furtado, M. (2005). *Pampas cat ecology and conservation in the Brazilian grasslands.*

Smith, J. A., Suraci, J. P., Hunter, J. S., Gaynor, K. M., Keller, C. B., Palmer, M. S., Atkins, J. L., Castañeda, I., Cherry, M. J., Garvey, P. M., Huebner, S. E., Morin, D. J., Teckentrup, L., Weterings, M. J. A., & Beaudrot, L. (2020). Zooming in on mechanistic predator–prey ecology: Integrating camera traps with experimental methods to reveal the drivers of ecological interactions. *Journal of Animal Ecology*, *89*(9), 1997–2012. https://doi.org/10.1111/1365-2656.13264

Swanson, A., Kosmala, M., Lintott, C., Simpson, R., Smith, A., & Packer, C. (2015). Snapshot Serengeti, high-frequency annotated camera trap images of 40 mammalian species in an African savanna. *Scientific Data*, *2*(1), 150026. https://doi.org/10.1038/sdata.2015.26

Tabak, M. A., Norouzzadeh, M. S., Wolfson, D. W., Sweeney, S. J., Vercauteren, K. C., Snow, N. P., Halseth, J. M., Di Salvo, P. A., Lewis, J. S., White, M. D., Teton, B., Beasley, J. C., Schlichting, P. E., Boughton, R. K., Wight, B., Newkirk, E. S., Ivan, J. S., Odell, E. A., Brook, R. K., … Miller, R. S. (2019). Machine learning to classify animal species in camera trap images: Applications in ecology. *Methods in Ecology and Evolution*, *10*(4), 585–590. https://doi.org/10.1111/2041-210X.13120

Tanwar, K. S., Sadhu, A., & Jhala, Y. V. (2021). Camera trap placement for evaluating species richness, abundance, and activity. *Scientific Reports*, *11*(1), 23050. https://doi.org/10.1038/s41598-021-02459-w

Tape, K. D., & Gustine, D. D. (2014). Capturing Migration Phenology of Terrestrial Wildlife Using Camera Traps. *BioScience*, *64*(2), 117–124. https://doi.org/10.1093/biosci/bit018

Thomas, M. L., Baker, L., Beattie, J. R., & Baker, A. M. (2020). Determining the efficacy of camera traps, live capture traps, and detection dogs for locating cryptic small mammal species. *Ecology and Evolution*, *10*(2), 1054–1068. https://doi.org/10.1002/ece3.5972

Trolle, M. (2003). Mammal survey in the Rio Jauaperí region, Rio Negro Basin, the Amazon, Brazil. *Mammalia*, *67*(1). https://doi.org/10.1515/mamm.2003.67.1.75

Viechtbauer, W. (2010). Conducting Meta-Analyses in *R* with the **metafor** Package. *Journal of Statistical Software*, *36*(3). https://doi.org/10.18637/jss.v036.i03

*Web of Science.* (2021). https://www.webofknowledge.com

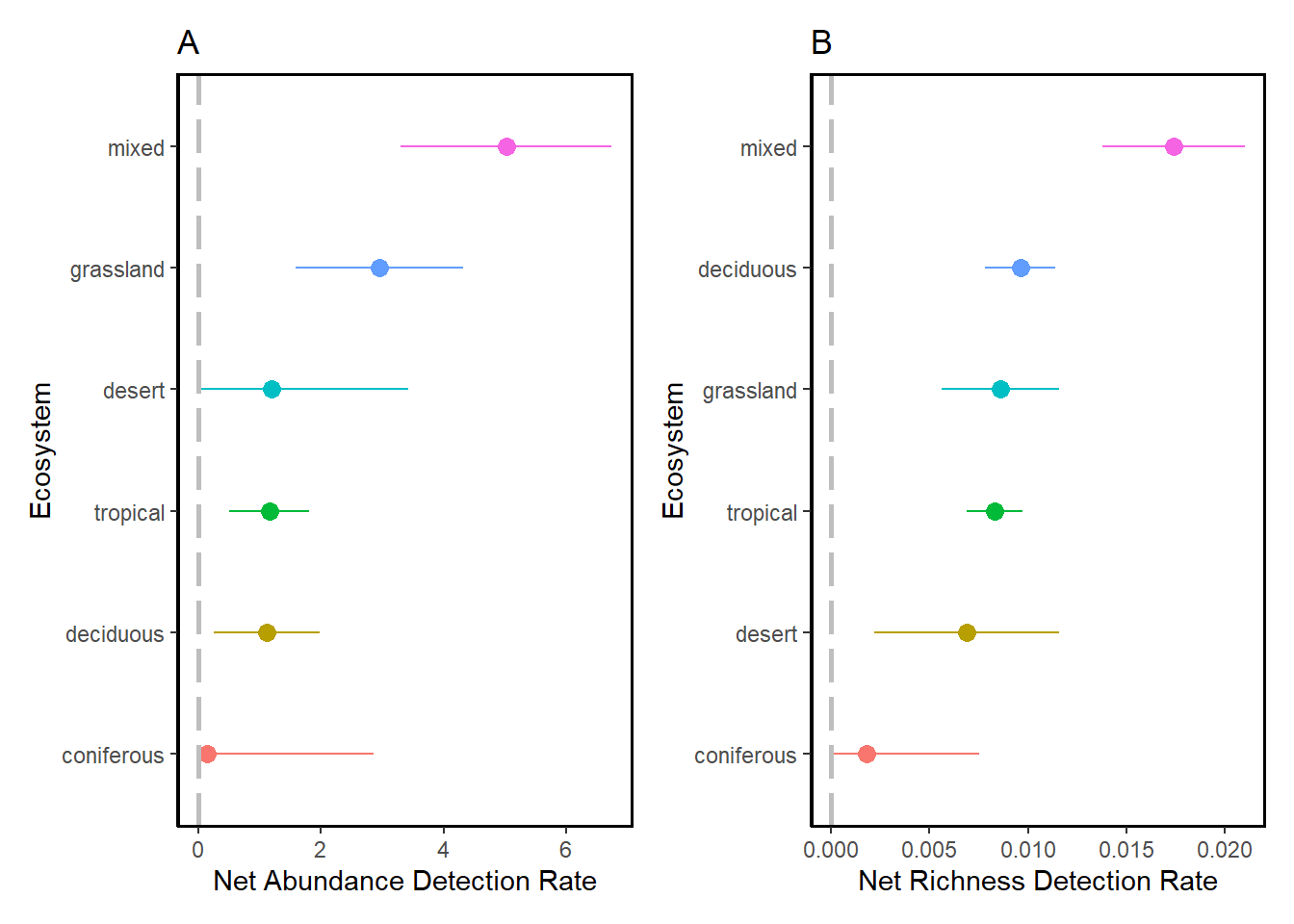
Wegge, P., Pokheral, C. Pd., & Jnawali, S. R. (2004). Effects of trapping effort and trap shyness on estimates of tiger abundance from camera trap studies. *Animal Conservation*, *7*(3), 251–256. https://doi.org/10.1017/S1367943004001441

Whytock, R. C., Świeżewski, J., Zwerts, J. A., Bara‐Słupski, T., Koumba Pambo, A. F., Rogala, M., Bahaa‐el‐din, L., Boekee, K., Brittain, S., Cardoso, A. W., Henschel, P., Lehmann, D., Momboua, B., Kiebou Opepa, C., Orbell, C., Pitman, R. T., Robinson, H. S., & Abernethy, K. A. (2021). Robust ecological analysis of camera trap data labelled by a machine learning model. *Methods in Ecology and Evolution*, 2041-210X.13576. https://doi.org/10.1111/2041-210X.13576

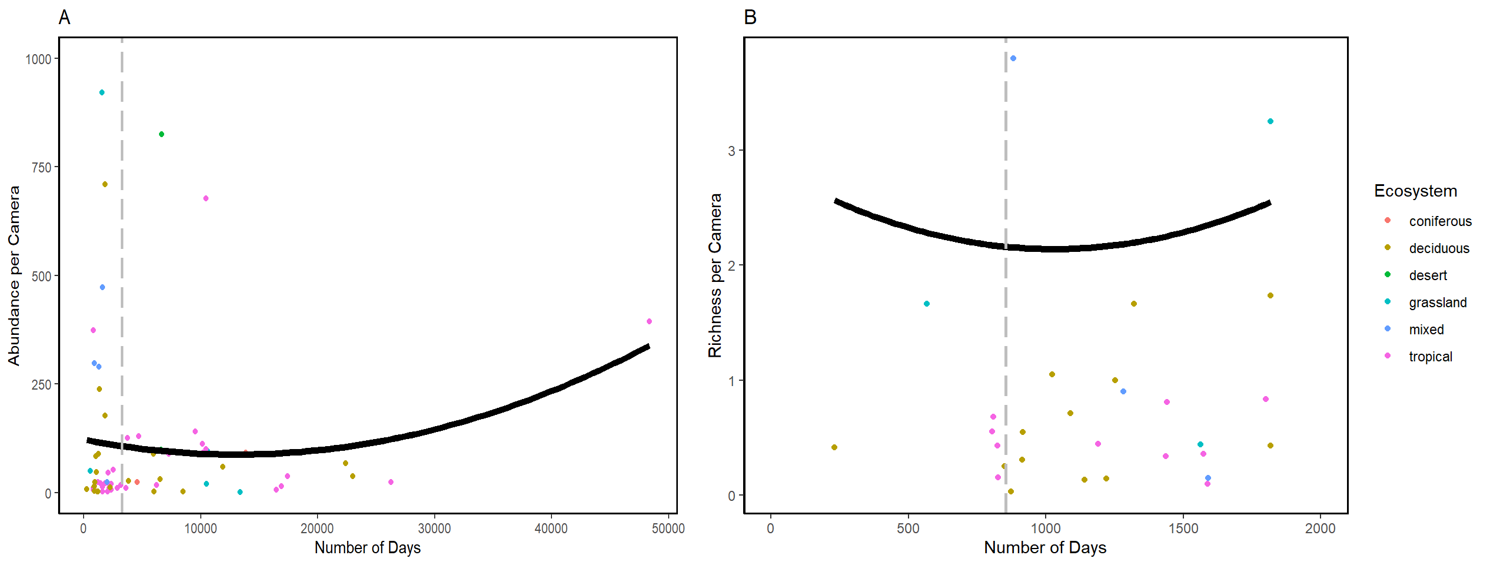
Wich, S. A., & Piel, A. K. (Eds.). (2021). *Conservation technology*. Oxford University Press.

Yasuda, M. (2004). Monitoring diversity and abundance of mammals with camera traps: A case study on Mount Tsukuba, central Japan. *Mammal Study*, *29*(1), 37–46. https://doi.org/10.3106/mammalstudy.29.37

**Figures and Tables**

****

**Figure 1. Forest plots showing estimated effect sizes from random-mixed model output for net abundance detection rate (A, animals/camera•day) and net richness detection rate (B, richness/camera•day) in 6 different ecosystems of study. Dots represent the meta-analytic mean and dashed lines represent the 95% confidence intervals.**

****

**Figure 2. Weighted regression plot showing the relationship between the number of animals per camera (A) and the number of species per camera (B) throughout the duration of the study (days), weighted by the variation in abundance or richness. Coloured dots represent the ecosystem of study. Black line represents smooth conditional mean and grey dashed line represents Minimum Trapping Effort (MTE).**

**Table 1. Mixed-effect model estimates and standard error (SE) for net abundance detection rate (number of animals/number of cameras/number of days) and net richness detection rate (number of species/number of cameras/number) are given. Ecosystem served as a moderator in the model. Significant p-Values are bolded.**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| ***Detection Rate*** | ***Ecosystem*** | ***Estimate*** | ***SE(±)*** | ***t-Value*** | ***95% CI.lb*** | ***95% CI.ub*** | ***p-Value*** |
| ***Abundance*** | ***Coniferous*** | 0.1417 | 2.6849 | 0.0528 | -5.2057 | 5.4891 | 0.9580 |
| ***Abundance*** | ***Deciduous*** | 1.0125 | 0.7594 | 1.3333 | -0.5000 | 2.5250 | 0.1864 |
| ***Abundance*** | ***Desert*** | 1.1951 | 2.1922 | 0.5452 | -3.1710 | 5.5612 | 0.5872 |
| ***Abundance*** | ***Grassland*** | 2.9580 | 1.3424 | 2.2035 | 0.2843 | 5.6317 | **0.0306** |
| ***Abundance*** | ***Mixed*** | 6.8013 | 1.5501 | 4.3876 | 3.7139 | 9.8886 | **<0.0001** |
| ***Abundance*** | ***Tropical*** | 1.0870 | 0.6160 | 1.7647 | -0.1398 | 2.3138 | 0.0816 |
| ***Richness*** | ***Coniferous*** | 0.0018 | 0.0063 | 0.2825 | -0.0108 | 0.0144 | 0.7784 |
| ***Richness*** | ***Deciduous*** | 0.0104 | 0.0018 | 5.8472 | 0.0069 | 0.0140 | **<0.0001** |
| ***Richness*** | ***Desert*** | 0.0069 | 0.0052 | 1.3454 | -0.0033 | 0.0172 | 0.1826 |
| ***Richness*** | ***Grassland*** | 0.0086 | 0.0034 | 2.5522 | 0.0019 | 0.0153 | **0.0127** |
| ***Richness*** | ***Mixed*** | 0.0153 | 0.0036 | 4.2010 | 0.0081 | 0.0226 | **<0.0001** |
| ***Richness*** | ***Tropical*** | 0.0077 | 0.0014 | 5.3384 | 0.0048 | 0.0106 | **<0.0001** |

**Table 2. A summary of ways camera trap data uses that can be incorporated in directing management actions. Implications and descriptions, as well as examples from the literature, are presented.**

|  |  |  |  |
| --- | --- | --- | --- |
| **Use in management** | **Implication** | **Description** | **Illustrative Studies** |
| Examining the types of species living in a region. | **Diversity change** | Monitor the extent of species diversity change to direct conservation action. | Rich et al. 2017 |
| Observing the impacts of changes in spatial and temporal dynamics of an ecosystem. | **Habitat change** | Examine habitat change, such as changes in vegetation dynamics, to make better-informed management decisions. | Sun et al. 2021 |
| Examining wildlife parameters in areas before and after restoration. | **Pre/post-restoration** | Compare and contrast protected and unprotected sites to examine species richness and community dynamics. | Littlewood et al. 2021  Oberosler et al. 2020 |
| Gathering information about how species in a region interact with artificial structures. | **Artificial structure** | Monitor the use of artificial construction such as electric fences and trenches, wildlife corridors, and acoustic, light-based, and agricultural deterrents that reduce human-wildlife conflict. | Green et al. 2018  Shaffer et al. 2019 |
| Assessing if threatened species have ceased or continue to exist in a given region. | **Presence/absence** | Assess the presence and absence of endangered or hard-to-identify species using camera traps. | Burns et al. 2017 |
| Gathering information about what animals are doing on a daily or in specific situations such as respond to stimuli. | **Animal behaviour** | Assess behaviour such as predator-prey interactions to guide future management efforts of endangered species. | Linkie and Ridout 2010 |

**Table 3. A definitions table for key terminologies.**

|  |  |
| --- | --- |
| **Terminology** | **Definition** |
| **Abundance (captures)** | Number of individual animals in a particular ecosystem. In this study, we used the number of captures and abundance interchangeably. |
| **Richness/diversity** | The number of different species present in an ecological community. |
| **Minimum Trapping Effort (MTE)** | The number of camera trap days required to record species of interest in an area |
| **Trapping Rate** | The number of photographs, of usually a particular species, over the duration of camera trapping in a particular area. |
| **Detection Rate** | The probability that a given individual will encounter a camera per unit of time. |
| **Incidence Rate Ratio** | An effect size measure consisting of the ratio of two rates. The first is a count in a particular parameter such as abundance or richness divided by sampling effort in terms of the number of cameras. Then, you divide the first rate by the total number of days the study was done to incorporate time into the effects size estimate. |
| **Net Abundance Detection Rate** | An incidence rate effect size measure calculated using species abundance per total number of cameras by total number of trapping days. |
| **Net Richness Detection Rate** | An incidence rate effect size measure calculated using species richness per total number of cameras by total number of trapping days. |