**Finding the sweet spot in camera trapping: a global synthesis and meta-analysis of net capture abundance and richness detection rates as an index of sampling effort.**

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**Abstract**

1. Camera traps have become one of the most common tools in wildlife biology, and their use typically includes documenting and measuring animal activity patterns and behaviour. Captures can be used to estimate population parameters such as presence/absence, relative abundance, and also local species richness.
2. A total of 292 full-text articles were returned from the Web of Science using the search terms Camera\* Trap\* and Richness\* or Diversity\*, and Rarefaction\* Curve\*. Full-text reviews of each for sampling effort in total number of days and total number of cameras provided 149 studies that reported animal abundance and species richness captured using this tool. We used an effect size measure of net abundance and net richness detection rate to examine how camera traps perform in different ecosystems.
3. The mean net positive effect of increasing the number of cameras on capture rates was positive, particularly in grasslands and mixed ecosystems. The man net richness of the animal communities in most ecosystems also increased with more cameras. However, Increasing the duration of trapping (number of days) did not consistently increase capture rate nor richness.
4. Camera trapping will continue to increase in use in ecology and evolution, and it is thus important to examine the efficacy of different experimental designs.

**Keywords**

Abundance, camera traps, diversity, meta-analysis, meta-regression, population estimates, richness, sampling effort.

**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 (O’Connell, Nichols, and Karanth 2011; Kelly 2008). Besides their use in wildlife research, camera traps have been used in studies that focus on behaviour (J. M. 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), population ecology, and occupation of human-built structures (O’Connell, Nichols, and Karanth 2011). Thus, camera trap data can be used to quantify many ecological parameters and help advance the theories of niche partitioning, habitat use, as well as various behavioural models (Smith et al. 2020; Frey et al. 2017). Camera traps are also a fundamental biodiversity monitoring tool in critical ecosystems such as the Serengeti (Swanson et al. 2015) and the amazon (Trolle 2003). Anthropogenic changes are impacting species re-distribution and range shifts (Franklin 2010) and we need to be able to measure biodiversity for mobile species in different ways. Camera traps provide a relatively easy method that enables us to do this and gather big data (Norouzzadeh et al. 2018; Carl et al. 2020). These data can then be used to evaluate the efficacy of survey designs (Kays et al. 2020) to support management and conservation.

Various crucial aspects can influence the number of species detected by camera traps, as well as the trapping rate (ratio of photographs to camera trapping duration) (Rovero and Marshall 2009). These include trigger speed, detection zone, recovery time, night detection, and battery consumption that can impact the collected data (Hughson and Darby 2010). Limitations of this method can also arise from camera models, placement and orientation, temperature differentials, and species behavioural responses (Meek, Ballard, and Fleming 2015). The factors can be summarized as trapping effort and trapping design and can affect estimates of abundance and diversity (Yasuda 2004; Wegge, Pokheral, and Jnawali 2004). Trapping or detection rate is a useful index for abundance and diversity estimates (Rovero and Marshall 2009; J. M. Rowcliffe et al. 2008; Silveira, Jácomo, and Diniz-Filho 2003). Minimum trapping effort (MTE) is another important factor for population estimates (Si, Kays, and Ding 2014). MTE refers to the number of camera trap days required to record species of interest in an area (Si, Kays, and Ding 2014) and varies extensively across studies. The number of camera traps used in a study is directly related to both trapping design and effort because a small number of cameras can result in low detection probabilities and affect the strength of population estimates (Foster and Harmsen 2012). The interplay amongst these elements provides us with an excellent opportunity to explore the relationship between trapping time, number of cameras, and richness estimates across the literature, globally. Knowing how trapping period and the number of cameras may influence the scope of fauna community assessments, both in abundance and diversity, provides us with insight into how to plan more effective experimental designs and gather better quantitative data that allow for an enhanced real-life representation of biodiversity across ecosystems worldwide.

Herein, we used a meta-analysis of the global peer-reviewed literature to test the hypothesis that sampling effort positively but non-linearly influences the net animal abundance and richness detection rate at a site or region sampled. We provided an overview of the relationship between sampling effort in days influenced by animal abundance per camera (number of captures per number of cameras), and species richness per camera (number of animals per number of cameras). The importance of ecosystems was also examined. Given that camera traps are increasingly being used in ecology and evolution in general (Tabak et al. 2019), our study provides an insight into the ‘sweet spot’ in potentially sampling many different ecosystems. The capacity for this method to provide meaningful and sufficient animal data will better inform conservation and management practices and fundamental theory.

**Methods**

***Literature review***

We conducted a systematic review using the terms Camera Trap\* and Richness\* or Diversity\*, and Rarefaction\* Curve\* in ISI Web of Science (WoS) (Web of Science, 2021). This search was done in May 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 (2009) (Supplementary material, Figure A). We used best practices to ensure that workflow and synthesis were reproducible and transparent (Bayliss and 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 in written in English (or 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 further reviewed for a measure of richness or diversity, the number of captures and/or duration of camera trapping (i.e. days). Data were extracted from article text or table. Variables such as the location of study, number of cameras, sites, and ecosystem were also recorded.

***Meta-Analyses***

All meta-statistical analyses were performed in R version 4.0.4 (R Development Core Team 2021)using the package *metafor* (Viechtbauer 2010). Effect sizes were calculated using the number of species and the number of animals (captures), which were independent event count variables, and used as incidence rates (PT Higgins, Li, and Deeks 2021) by division against the total number of cameras and the total number of days via the function *escalc*. Mean values and the 95% confidence intervals for each effect size were then plotted on a forest plots for each group of estimates by ecosystem. Random-effects models (*rma)* were applied to analyze estimated values and stand error for the number of animals/number of cameras/number of days and number of species/number of cameras/number of days using the method = "ML", test = “knha" with ecosystem serving as moderator. Maximum likelihood (ML) refers to a method of estimation so that given the particular model the likelihood of producing that similar to ones that were actually observed are maximized (Cam 1990). Hartung and Knapp (knha) is a test statistic based on the estimation function for the variance of the treatment overall effect estimator and keeps the prescribed significance level much better compared to other test used in random-effect models (Hartung and Knapp 2001). Regression models were also applied to analyze estimated values for the number of animals/number of cameras and the number of species/number of cameras over the total number of days. The method and test remained the same as above. 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)

**Results**

A total of 149 articles were included in the meta-analysis. Codes and final data are published on Zenodo (Ghazian and Lortie, 2021). The most common ecosystems for the studies were deciduous (25 studies) and tropical (38 studies). A random-effect model was fit to the calculated animal abundance effect size estimates and resulted in an asymmetric funnel plot suggesting systematic differences between the studies that was confirmed by significant heterogeneity between the groups (Q = 1445220667.62, p<0.0001). Ecosystem was a significant moderator in the model (F = 3.056, p = 0.0105, *df* = 6) and net effect of testing for trapping effort using animal abundance resulted in significantly positive estimates only in grassland and mixed systems (Figure 1 and Table 1). A similar random-effect model was also fit to animal richness estimates where significant heterogeneity between groups was also observed (Q = 1131929994.36, p<0.0001). Ecosystem as a moderator was also significant (F = 15.48, p<0.0001, *df* = 6) and net effect of testing trapping effort using species richness calculated estimates was significantly positive in all ecosystem (Figure 1, Table 1), except in desert and coniferous forest. A meta-regression analysis was conducted for the number of animal/number (Figure 2, Table 2) of cameras over the total number of days, which resulted in significant heterogeneity between groups (Q = 549352.8229, p<1000). The same analysis was so conducted for species richness/number of cameras (Figure 2, Table 2) and showed significantly positive heterogeneity (Q = 151603.35, p<0.0001). However, the total number of days was not shown to be a significant moderator in predicting net positive animal abundance or richness estimates.

**Discussion**

The importance of effective wildlife detection and estimating biodiversity is fundamental to community assessment of resident fauna and ultimately the management, conservation, and restoration of many systems globally. The hypothesis that increasing sampling effort in terms of the number of cameras per number of days deployed was supported in our study in most systems, suggesting that camera traps are an effective measurement tool to estimate the relative abundance of animals and local species richness. Hence, this synthesis demonstrated strong support for careful consideration of parameters such as the number of cameras and the duration of study to obtain accurate population estimates that are a percise representation of the real-life biodiversity of a given region.

Our results demonstrate that camera traps work globally in virtually all ecosystems. Here, we did not only examine the relative importance of days but also the net positive effects of incidence capture and richness rates, which suggest that sampling effort can be influenced by the number of camera traps as well as the number of days. This idea was supported here in terms of the number of captures specifically in grasslands and mixed ecosystems and in terms of animal richness in almost all ecosystems. According to (Ferreras et al. 2017) success in detecting all the species in the system depends on many factors, including the number of cameras. They too suggest that it is more efficient to deploy more camera traps for a shorter duration rather than to deploy fewer camera traps for a longer one, for any given number of camera trap days. There is an enormous expansion in the number of sites that camera traps are being used and most literature acknowledges the fact that one cannot discuss the notion of the number of cameras without talking about how far apart cameras were placed and how extensively the site was studied. Trap placement designs are important and the use of systematic trap placement design or a design suited to the habitat may be appropriate if the primary goal of the survey is richness estimation (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, Nichols, and Karanth 2011). The interrelatedness of camera trap placement and the number of cameras is not an idea that we explored *per se*, though is integral in maximizing the potential of camera traps for wildlife monitoring. Understanding how many cameras are needed and how far apart they need to be placed relative to the particular ecosystem of study will ensure more precise wildlife and biodiversity monitoring of any given region.

(Kelly 2008; Rovero and Marshall 2009; Wegge, Pokheral, and Jnawali 2004) Sampling effort is a critical design topic in all of ecology and evolution and particularly in field studies. In this study, we explored the relationship between sampling effort and the total number of trapping days and found increasing the number of trapping days past a certain point did not increase the capacity of cameras to detect more animals neither in abundance nor diversity. This is directly related to the notion of MTE (Si, Kays, and Ding 2014), as previously discussed. Differences in the number of camera trap days across studies are related to animal richness at the site. MTE can be affected by habitat, local characteristics, target community, and sampling strategy, including camera spacing, presence or absence of bait, and camera models (Kelly 2008; Rovero and Marshall 2009; Wegge, Pokheral, and Jnawali 2004). According to Si, Kays, and Ding (2014), increasing the number of camera sites and rotating cameras to new sites is more efficient for richness estimates as opposed to leaving cameras at the same site for a longer duration of time. This is because regardless of the system of study, after a certain number of days, species rarefactions level off and a longer trapping period does not result in increased diversity. Hence, to increase the likelihood of detection, we suggest considering the above when designing the study and placing more attention on increasing the number of sites and cameras, and rotating cameras, as opposed to increasing the duration of trapping.

**Implications**

Anthropogenic changes are affecting species distribution in ways that intensive monitoring of local species in different regions will be critical for the maintenance of biodiversity and the implementation of management practices in the upcoming years. Our results offer new and exciting insight into the utility of camera traps as a tool in monitoring changes in wildlife ranges and show promising outcomes for conservation and restoration strategies. Camera traps are a powerful instrument whose popularity in wildlife research has increased tremendously (Forrester et al. 2016). In the years to come, not only will their popularity increase as a stand-alone tool but we will also see a rise in their cross implementation in AI and machine-learning environmental monitoring studies (Tabak et al. 2019; Willi et al. 2019). Future challenges for researchers will include well-planned experimental designs to maximize the extent of surveys and finding common data formats to facilitate the easier transfer of storage and data.

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**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.

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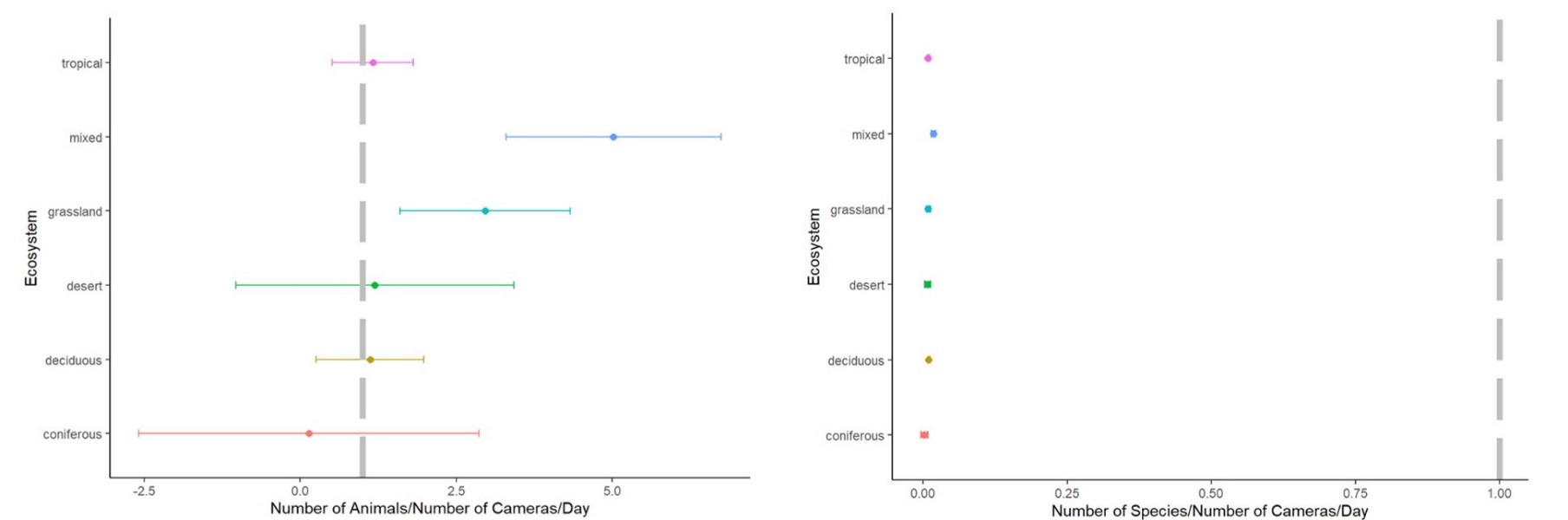
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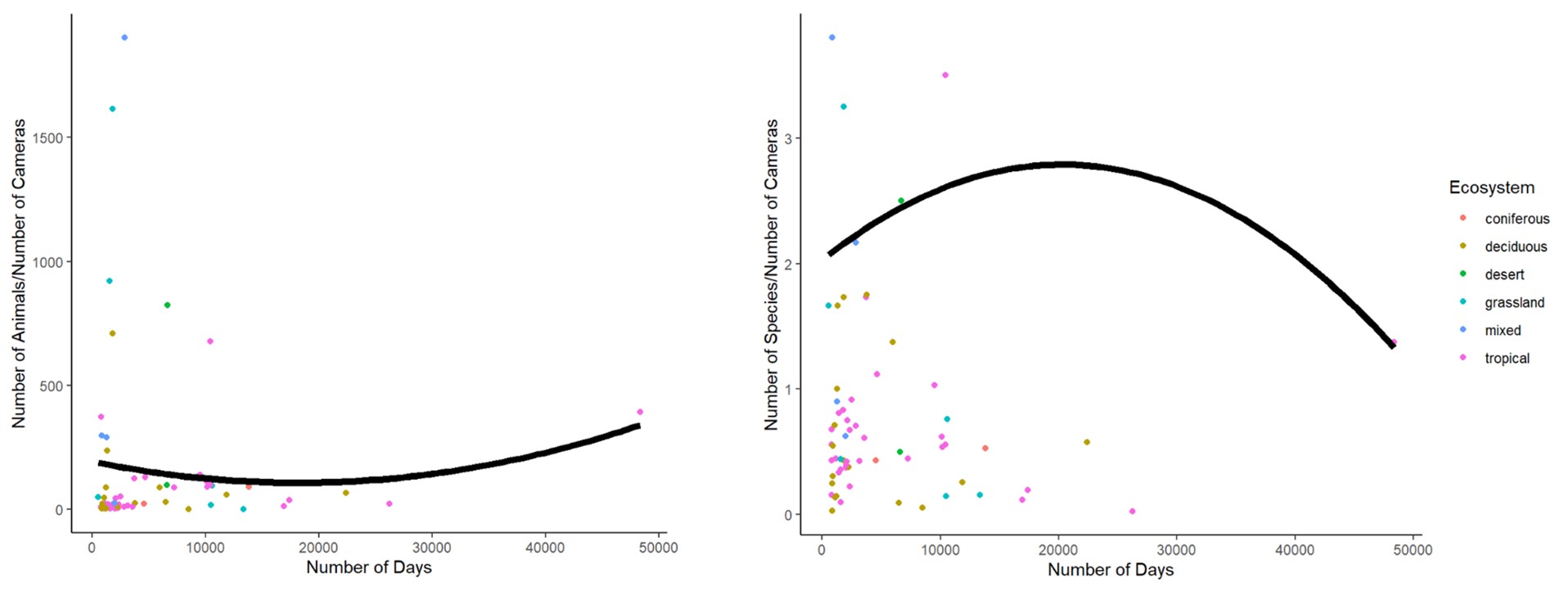
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**Figures and Tables**



**Figure 1. Forest plots showing estimate effect sizes from random-mixed model output for the number of animals/number of cameras/number of days (left) and number of species/number of cameras/number of days (right) in 6 different ecosystems of study. Coloured dots represent the meta-analytic mean and dashed lines represent the 95% confidence intervals.**



**Figure 2. Meta-regression plot showing the relationship between the number of animals/number of cameras (left) and the number of species/number of cameras throughout the duration of the study (days). Smoothed conditional mean is fitted using a random-mixed model using the method maximum likelihood. Coloured dots represent the ecosystem of study.**

**Table 1. Mixed-effect model estimates and standard error (SE) for animal abundance (number of animals/number of cameras/number of days) and animal richness (number of species/number of cameras/number) are given for each ecosystem. Significant p-Values are bolded.**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Animal Abundance** | | | | | | |
| **Ecosystem** | ***Estimate*** | ***SE(±)*** | ***t-Value*** | ***95% CI.lb*** | ***95% CI.ub*** | ***p-Value*** |
| **Coniferous** | 0.1417 | 2.6849 | 0.0528 | -0.2057 | 5.4891 | 0.9580 |
| **Deciduous** | 1.0125 | 0.7594 | 1.3333 | -0.5000 | 2.5250 | 0.1864 |
| **Desert** | 1.1951 | 2.1922 | 0.5452 | -3.1710 | 5.5612 | 0.5872 |
| **Grassland** | 2.9580 | 1.3424 | 2.2035 | 0.2843 | 5.6317 | **0.0306** |
| **Mixed** | 6.8013 | 1.5501 | 4.3876 | 3.7139 | 9.8886 | **<0.0001** |
| **Tropical** | 1.0870 | 0.6160 | 1.7647 | -0.1398 | 2.3138 | 0.0816 |
| **Animal Richness** | | | | | | |
| **Ecosystem** | ***Estimate*** | ***SE(±)*** | ***t-Value*** | ***95% CI.lb*** | ***95% CI.ub*** | ***p-Value*** |
| **Coniferous** | 0.0018 | 0.0063 | 0.2825 | -0.0108 | 0.0144 | 0.7784 |
| **Deciduous** | 0.0104 | 0.0018 | 5.8472 | 0.0069 | 0.0140 | **<0.0001** |
| **Desert** | 0.0069 | 0.0052 | 1.3454 | -0.0033 | 0.0172 | 0.1826 |
| **Grassland** | 0.0086 | 0.0034 | 2.5522 | 0.0019 | 0.0153 | **0.0127** |
| **Mixed** | 0.0153 | 0.0036 | 4.2010 | 0.0081 | 0.0226 | **<0.0001** |
| **Tropical** | 0.0077 | 0.0014 | 5.3384 | 0.0048 | 0.0106 | **<0.0001** |

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Animal Abundance** | | | | | | |
|  | ***Estimate*** | ***SE(±)*** | ***t-Value*** | ***95% CI.lb*** | ***95% CI.ub*** | ***p-Value*** |
| **Intercept** | 141.6745 | 45.1943 | 3.1348 | 51.5144 | 231.8346 | **0.0025** |
| **Days** | -0.0003 | 0.0046 | 0.9515 | -0.0095 | 0.0089 | 0.9515 |
| **Animal Richness** | | | | | | |
| **Intercept** | 0.7377 | 0.1076 | 6.8576 | 0.5231 | 0.9523 | **<0.0001** |
| **Days** | 0 | 0 | -06081 | 0 | 0 | 0.5451 |

**Table 2. Meta-regression model estimates and standard error (SE) for animal abundance (number of animals/number of cameras) and animal richness (number of species/number of cameras) over the total number of days are given for each ecosystem. Significant p-Values are bolded.**

**Supplementary Appendix**

Papers obtained through database searching (Web of Science) Keywords:

Camera\* Trap\* AND Richness\*, Diversity\*, and Rarefaction\* Curve\*

(n= 716)

(n = 1090)

## Identification

Papers obtained from other sources, such as book chapter bibliographies

(n= 0)

## Eligibility

Records after duplicates removed   
(n = 557)

Records excluded for: relevance, review, opinion or idea paper, focus on one species, qualitative, not English.

Records screened by abstract (n = 557)

## Screening

Full-text articles excluded:

Not reporting richness or diversity, number of records, and any measure of duration, aquatic studies.

Full-text articles assessed for eligibility (n = 292)

(n = )

Include in synthesis

(n = 149)

## Included

Extracted data:

Location (latitude, longitude), camera trap days, number of records, animal richness, common name, scientific name, year, number of cameras, presence of bait, number of cameras, number of sites, and ecosystem.

**A. PRISMA diagram used for camera trapping effort systematic review (Moher et al. 2009). Search done with keywords: Camera\* Trap\* AND Richness\*, Diversity\*, and Rarefaction\* Curve\* in May of 2021.**