Finding a clear signal: a systematic review of desert radio telemetry research.

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Radio telemetry is a common tool to monitor animals in many ecosystems. Radio telemetry, or radio tracking, typically uses a tag or collar with a radio transmitter attached to an animal that is monitored by researchers with a receiver. This technique is used for research in many disciplines such as wildlife ecology or conservation biology. Within desert ecosystems, this approach has been used since the 1960s in many different research capacities. Many desert species exist at low density and can range widely within a region due to scarce resources, which can make radio telemetry a useful method to use in these environments. Here, we examined the peer-reviewed literature to assess how radio telemetry is used in deserts. Using the Web of Science with additional search validation on Google Scholar to formally summarize this research, we found 97 studies that fit our criteria. Most primary studies used radio telemetry to examine individual behavior and/or habitat use. The majority of published studies were done in the United States. The most common classes of animal studied were mammals (29.9 % large mammals and 25.8 % small mammals). Most species studied were classified as 'least concern' for risk status. Vhf radio telemetry devices predominated the technology selected (80.4 %) whilst GPS devices were used in 19.6 % of studies. Radio telemetry devices are an effective tool to survey individual animals and animal populations in harsh desert environments. However, future research can be improved using these tools to improve reproducibility encourage data reuse and comparison between studies. We encourage authors using radio telemetry to publish their data and include details of their study area and tracking methods to accomplish these goals.

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Abstract

Radio telemetry is a common tool to monitor animals in many ecosystems. Radio telemetry, or radio tracking, typically uses a tag or collar with a radio transmitter attached to an animal that is monitored by researchers with a receiver. This technique is used for research in many disciplines such as wildlife ecology or conservation biology. Within desert ecosystems, this approach has been used since the 1960s in many different research capacities. Many desert species exist at low density and can range widely within a region due to scarce resources, which can make radio telemetry a useful method to use in these environments. Here, we examined the peer-reviewed literature to assess how radio telemetry is used in deserts. Using the Web of Science with additional search validation on Google Scholar to formally summarize this research, we found 97 studies that fit our criteria. Most primary studies used radio telemetry to examine individual behavior and/or habitat use. The majority of published studies were done in the United States. The most common classes of animal studied were mammals (29.9 % large mammals and 25.8 % small mammals). Most species studied were classified as 'least concern' for risk status. Vhf radio telemetry devices predominated the technology selected (80.4 %) whilst GPS devices were used in 19.6 % of studies. Radio telemetry devices are an effective tool to survey individual animals and animal populations in harsh desert environments. However, future research can be improved using these tools to improve reproducibility encourage data reuse and comparison between studies. We encourage authors using radio telemetry to publish their data and include details of their study area and tracking methods to accomplish these goals.

Introduction

Radio telemetry, frequently termed radio tracking, is a common survey method for animal behavior and wildlife ecology studies (Cochran *et al.* 1963, Swanson *et al.* 1975, Sokolov 2011). A wildlife radio telemetry system consists of a radio transmitter or other radio telemetry device attached to an animal and a receiver to pick up the signal of the transmitter (Cochran *et al.* 1963, Swanson *et al.* 1975, Brand *et al.* 1975, Brugnoli *et al.* 2008). Most often the device is attached using a collar, but other attachment methods such as harnesses, backpacks, or surgical implantation can also be used (Taylor *et al.* 2004, Schorr *et al.* 2011). The animal can then be located by searching for the specific signal of the transmitter using the receiver. Radio telemetry was original developed in the 1960s using Very High Frequency (VHF) transmitters (Cochran *et al.* 1963). These early transmitters had a limited range and were usually large and this limited their use to larger animal species (Cochran *et al.* 1963, Kaczensky *et al.* 2010, Sokolov 2011). However, even with these limited capabilities, radio telemetry was a useful tool for studying animals. Once the transmitters were attached, rare or elusive animals could be readily located and individuals of a species could be identified and observed repeatedly (Cochran *et al.* 1963, Swanson *et al.* 1975, Brugnoli *et al.* 2008). As technology advanced, transmitter size decreased thereby expanding the range of species that could be studied using this method. Today transmitters are small enough that small mammals, birds, and even insects and other arthropods can be effectively tracked (Brand *et al.* 1975, Sokolov 2011, Kays *et al.* 2015). The range of these systems has also increased to the point that animals can be tracked many kilometers away (Meretsky *et al.* 1992, Brugnoli et *al.* 2008, Sokolov 2011). Species that travel long distances, such as the California condor, can now be tracked throughout their range (Meretsky *et al.* 1992, Kays *et al.* 2015). Some radio telemetry systems can even track collared animals automatically through the use of receiving stations within a region (Johansson *et al.* 2011, Kays *et al.* 2015). Technology aside, this is a rapidly evolving research technology and important for both basic science and conservation (Sokolov 2011, Kays *et al.* 2015, Wilson *et al.* 2015).

Though the basic principle of radio telemetry has remained the same, the technology used continues to evolve and this has introduced other research opportunities. Though VHF transmitters are still used in the field, the development of the Global Positioning System (GPS) now provides relatively more accurate tracking for wildlife researchers but typically is more expensive. GPS tracking allows the radio telemetry device to determine the exact position of an animal (Keating *et al.* 1991, Fuller *et al.* 1995, Kaczensky *et al.* 2010, Sivakumar *et al.* 2010). Many systems allow a position to be taken at regular intervals automatically, and this sampling can be used to measure animal movements (Kaczensky *et al.* 2010, Sivakumar *et al.* 2010). Some GPS transmitters will regularly send data directly to researchers (Keating *et al.* 1991, Rodgers *et al.* 2001). Other systems require that the data be downloaded either by radio transmission or directly when the unit is recovered (Rodgers *et al.* 2001, Sivakumar *et al.* 2010). GPS units often combine with VHF transmitters to either allow the recorded data to be downloaded or to aid in finding the unit for recovery (Keating *et al.* 1991). Thus, current studies can use either or both technologies depending on specific research needs and budget (Skupien *et al.* 2016).

Both VHF and GPS radio telemetry systems provide location data, and this coupled methodology is often used in studies to determine animal species range and movement (Brugnoli *et al.* 2008, Kaczensky *et al.* 2010, Sivakumar *et al.* 2010). Both daily and long-term movement can be determined by setting the interval appropriately to estimate home range and habitat use (Meretsky *et al.* 1992 Brugnoli *et al.* 2008, Larroque *et al.* 2015). If multiple individuals are tagged in an area, home range overlap and interactions can also be studied (Brugnoli *et al.* 2008, Schorr *et al.* 2011, Long *et al.* 2014). Species can be tracked to determine their interaction with various aspects of their environment including aspects such as available resources and human development (Dyer *et al.* 2001, Brugnoli *et al.* 2008, Johnson *et al.* 2013). Behavior is another topic commonly studied using this method, including individual repeated behavior and time budgets (Swanson *et al.* 1976, Sokolov 2011, Connor *et al.* 2016). In addition to location, radio telemetry devices can be outfitted with additional sensors to record data such as body temperature, motion, and mortality (Taylor *et al.* 2004, Lee *et al.* 2005, Murray 2006, Sokolov 2011). With different protocols and relocation methods, radio telemetry can be used to examine a wide variety of wildlife ecology questions (Allen *et al.* 2013, DeMay 2015).

Radio telemetry is commonly used in desert ecosystems (Meretsky *et al.* 1992, Krausman *et al.* 2004, Bleich *et al.* 2009, Schorr *et al.* 2011, Oppel *et al.* 2015). Desert ecosystems have a high number of endangered and threatened species (Flather *et al.* 1998, Meretsky *et al.* 1992, Germano *et al.* 2011, Schorr *et al.* 2011). These species are often of concern to land managers who may need information on behavior and habitat use (Sokolov 2011, Connor *et al.* 2016). Because resources are scarce, animal that live in these areas are often present at relatively low densities and can have to travel long distances for water or food making radio telemetry the most effect means to study these species (Meretsky *et al.* 1992, Schorr *et al.* 2011). In this systematic review, we examined the peer-reviewed literature to assess how radio telemetry was used in deserts. A summary of the general practices of working in these ecosystems with radio telemetry will be useful to researchers planning similar studies. The following objectives were examined herein for desert radio telemetry studies:

1. To determine the method of use for radio telemetry devices used in deserts.

2. To categorize the types of ecological questions examined using radio telemetry.
3. To summarize the frequency that different desert taxa have been studied with radio telemetry and the frequency of the conservation status of study species.
4. To summarize the variety of protocols and designs used.

By better understanding radio telemetry use in desert ecosystems, researchers and land managers can better determine if radio telemetry fits the needs of their study and assess the frequency of radio telemetry options available from the published literature. This synthesis will also facilitate reuse existing radio telemetry data by highlighting commonalities. Scientific synthesis of topics and of tools is an important mechanism to both summarize and improve future research, and formal systematic reviews provide an excellent indication of the scope of testing and gaps (Lortie 2014). There have been extensive narrative reviews of radio telemetry research in general but none for deserts and no systematic reviews to date.

Methods

We searched the Web of Science (Thomson Reuters) using the terms ‘radio tracking AND desert’, and ‘radio telemetry AND desert’ in October 2016. This search returned a total of 165 studies. Topics unrelated to ecology were excluded such as medical and atmospheric sciences. These studies were then downloaded in full and reviewed to determine if they were relevant to the objectives of this review. Studies were excluded if they did not include radio telemetry, did not take place in an arid or semi-arid environment, were reviews, or did not examine primary research data. This lead to the exclusion of 68 studies thereby retaining 97 papers remaining for further detailed analyses to address objectives. This process was illustrated with a PRISMA report (fig 1). TJN performed the search strategy. Each paper was then categorized by a set of higher-order ecological hypotheses, and studies that examined multiple hypotheses were also documented (See Supporting information for a list of study classifications). The study species was extracted including the Latin and common names, taxa, and reported species risk status. The number of species examined within each study was also recorded. Sample sizes, animal life stage, attachment method, radio telemetry device type, study duration, and scale of study were recorded. The country and desert were recorded, and geographical coordinates were noted in papers that included them, and these location data were mapped using R (version 3.3.2) to create an evidence map (McKinnon *et al.* 2015). For studies that did not list coordinates, Google Earth was used to map the location of a study and determine its geographic coordinates. The complete dataset can be found on figshare: https://figshare.com/articles/radio telemetry_review_full_details_csv/4725499. Differences in the relative frequency of the major categories of the data extract were compared using Chi-square tests to determine patterns in the use of radio telemetry for the various potential factors. All analyses and graphing were performed using R (version 3.3.2) using the ggplot2 and chisq.test packages. All R code used is provided on GitHub: https://cjlortie.github.io/telemetry.review/

Results

A total of 97 studies that had been done in deserts using radio telemetry within the research domains of ecology, conservation, wildlife biology, and environmental studies were retained for this review. The studies were located in desert environments throughout the world; however, there were clusters of studies. The largest proportion of studies was in the United States (36 %, n = 35), Australia (16.5 %, n = 16), and South Africa (7.2 %, n = 7) (Fig 2). The main ecological purpose of these studies was individual behavior and habitat use with 39.2 % and 37.1 % respectively (Fig 3, Chi-square test, $\chi 2 = 82.814$, $p < 0.001$). Slightly over a third of the studies examined only one hypothesis (39.2 %), but the majority examined 2 or 3 (59.8%). Amongst those that studied more than one, behavior (40.7 %), habitat use (28.8 %) and thermoregulation (10.2 %) were the most common secondary ecological question examined. The most common classes of animal studied were large and small mammals (29.9 % and 25.8 % respectively), followed by birds (21.6 %) and reptiles (20.6 %) (Fig 3). Most studies focused on only one species (87.6 %). Most species studied were classified as 'least concern' for risk status by the International Union for Conservation of Nature (IUCN) (70 %, n = 64) followed by species classified as vulnerable (20.6%, n = 20). Endangered and threatened species were also studied in a smaller proportion of studies.

The number of individuals sampled varied between studies. Hypotheses examining demographics and distribution had a higher mean sample sizes compared to other study types in the review (One-way ANOVA, F = 3.2941, p <0.01) (Fig 4). Most studies utilized vhf radio telemetry devices (80.4 %, n = 78, Chi-square test, X2 = 35.887, p > 0.001). GPS devices were used in 19.6 % of studies (n = 19). The GPS devices were used exclusively in studies that examined behavior and habitat use (Fig 5, Chi-square test, $\chi 2 = 35.9$, $p = 0.0001$). GPS and VHF devices were used for similar purposes for these types of studies. Most studies were local in scale, i.e. at the scale of several square kilometers (79.4 %, n = 77). Duration of studies also varied. Studies examining demographics and distribution had a longer average duration.

Discussion

Radio telemetry is a common method used for ecology and wildlife biology studies in most ecosystems globally including desert environments (Bleich *et al.* 2009, Sokolov 2011, O'Mara *et al.* 2014, Oppel *et al.* 2015). Despite the harsh environmental conditions, such as high temperature, found in desert environments, no study reported that these conditions influenced the radio telemetry systems performance or failure rates. This suggests that researchers do not need to make any special considerations when planning studies for this environment, such as collaring extra animals in anticipation of multiple transmitters failuring (Sokolov 2011, O'Mara *et al.* 2015). This is likely to the robust standards that devices are built to, although the low humidity of the desert may be beneficial as well (Sokolov 2011, O'Mara *et al.* 2015). Alternatively, device failures may be underreported in published studies. The majority of the studies we reviewed examined animal behavior and habitat by using detailed, individual observations. This included both studies that used VHF transmitters as well, as those that used GPS transmitters, indicating that both types can be a relatively precise research instrument in deserts (Swanson *et al.* 1976, Sokolov 2011, Kay *et al.* 2015). The most common classes of animal studied were large and small mammals suggesting that both highly mobile organisms, and those with a more localized range within a desert region can be examined using these technologies and survey techniques. The exact protocol and study design used varied based on the scientific purpose and on studies species. Based on our findings, radio telemetry can be a useful tool for ecology and wildlife biology studies in particular due to the detailed datasets it can collect (Swanson *et al.* 1975, Brugnoli *et al.* 2008).

Contemporary radio telemetry technologies can be applied to a wide-range of taxa (Kay *et al.* 2015). However, in deserts mammals were the primary set of species examined to date. This is a pattern that is common with many types of studies because mammals are often the most

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prominent species for researchers to study in an environment (Small 2011). Birds often rank with mammals as charismatic organisms and were fairly well represented in desert studies though not as studied as mammals. (Small 2011). Reptiles were represented fairly well in this study but, as with birds, were not studied as well as mammals. This is important to note as animals vary in their sensitivity to environmental change (McKinney 2008) and by instrumenting mostly mammals we are potentially skewing our understanding of how species respond to change or use desert ecosystems. Finally, there are many non-mammalian endangered species radio telemetry could be an ideal tool to enhance detailed and specific species biology knowledge for conservation purposes (Small 2011). Admittedly, the feasibility of attaching collars to a study species is an important consideration. When radio telemetry was first developed for wildlife radio telemetry the size of the devices limited studies to large mammals. This was because the attached device cannot exceed a certain percentage of the animal's mass, usually no more than 5-10%, to minimize the effect they have on animal behavior and survival (Cochran *et al.* 1963, Kaczensky *et al.* 2010, Sokolov 2011). With advances in radio telemetry technology, devices can now be made smaller allowing them to be used on small mammals, birds, reptiles, and arthropods (Brand *et al.* 1975, Sokolov 2011). Consequently, radio telemetry should be explored as a tool for many taxa in desert ecosystems to better shape our understanding of animal responses to change and to broaden available data for future syntheses including species distribution models (Rice *et al.* 2013) and habitat use estimates (Christ *et al.* 2008).

Radio telemetry is a useful tool for conservation biologists because the behavior and habitat use data needed to make management decisions for species can be collected in effectively designed surveys. Deserts have a high number of threatened and endangered species (Flather *et al.* 1998, Meretsky *et al.* 1992, Germano *et al.* 2011), but the majority of studies reviewed did not focus on species threatened in some way. Radio telemetry can also provide larger-scale pattern data relevant to management and is commonly used to study species of concern in many other ecosystems such as forests and grasslands (Burgess *et al.* 2009, Sokolov 2011, Connor *et al.* 2016). Importantly, the classification of a species as endangered does not guarantee that the study will be best served by the use of radio telemetry because other aspects of the species besides behavior or habitat may need to be studied. Acquiring permits to instrument listed species can also be a challenge in many jurisdictions. Some desert species are also locally threatened rather than globally threatened (Phelan *et al.* 2005). In addition these are species who are not uncommon on a global level, but may have local populations or subspecies which are threatened (Wells *et al.* 2010). The bighorn sheep (*Ovis canadensis*) is a species that lives in the desert, and it is a species of concern in certain areas but classified by the IUCN as 'least concern' (Bleich *et al.* 2010, Wells *et al.* 2010). Global risk status thus does not necessarily include these locally threatened populations (Wells *et al.* 2010). Radio telemetry is less invasive than many survey methods, such as mark-recapture surveys, but it does involve some handling and the attachment of a device the animal is not accustomed to (Bird *et al.* 2014, Habib *et al.* 2014). This may lead to fewer radio telemetry studies being permitted by land managers (Habib *et al.* 2014). Identifying the most relevant data for conservation of species is an important first step. However in deserts, the relatively low frequency of study of listed species suggests that additional research on a variety of animals would benefit the assessment of general ecosystem-level priorities and impacts.

Sample sizes are a critical issue in many domains of animal research. Often sample sizes in animal-focused studies are relatively lower than other domains of research such as plant ecology for instance (Elzinga et al. 2001). Animal studies present unique challenges because of their mobility, and data at larger scales are often needed. Some animals do have relatively small or restricted distribution patterns with a research region of interest or conservation (Meretsky *et al.* 1992, Krementz *et al.* 2012, Liminana *et al.* 2012), and for desert research, different ecological research topics both assume and sometimes need different levels of sampling and replication. A demographic survey will require a much higher sample size than a relatively more limited study of body temperature because demographic studies by definition will need to get a representative sample of the population (Elzinga *et al.* 2001, Robinson *et al.* 2016). As would be expected there was some variation in sample size of studies examining the same ecological hypothesis. This is likely due to the differences between species and the differences in radio telemetry device required for each species as well as simple variation in study design (Taylor *et al.* 2004, Brugnoli *et al.* 2008, Schorr *et al.* 2011). Additionally the collection of radio telemetry data can be time consuming which can limit the number of animals that can be feasible tracked The commonness of a species, ease of capture, and the cost and/or ease of deployment for the device used also play a part in the extent of animals sampled (Sokolov 2011).

Radio telemetry studies can be a wealth of information for researchers in any environment, however we observed several missed opportunities among the desert radio telemetry studies reviewed. One such opportunity that was not reported in most of the studies was whether or not all of the individuals of the study species in the study area were collared or if there were some remaining individuals that were not. This is important because whether or not all animals in an area are collared can have an effect on any calculation of interaction between individuals or of population size or density (Brugnoli *et al.* 2008, Schorr *et al.* 2011, Bird *et al.* 2014). These are important ecological measures for desert ecosystems that are high stress, are patchy, and sometimes have animals at low density (Meretsky *et al.* 1992, Schorr *et al.* 2011).

Home range sizes are another example of potential measures available if more data is reported. Home range calculations were reported for many studies, usually calculated using the Minimum Convex Polygon method (MCP), though other methods such as Least Convex Hull or kernel density estimators were used either alone or in combination with MCP. However, several studies did not report home range size where it could have been calculated using the available data. Including these data would also allow for comparisons of home range area between radio telemetry studies of related species and increase the potential that the data from an individual study will be reusable (Schorr *et al.* 2011). Desert animal studies should include estimates of spatial extent of study and estimate total population sizes for the study area whenever possible because the ability to connect different studies would be useful for examining larger conservation issues (Goldingay 2015, Lopez-Lopez 2016). Another missed opportunity is the availability of data from these studies. Only around 10% of the papers reviewed made their data available to other researchers. Publishing data is important because it supports data reuse and makes large scale ecological research possible, a plus for conservation (Campbell *et al.* 2015, Lopez-Lopez 2016). Radio telemetry data can be published on tracking specific databases such as Movebank or Zoatrack, or on more general databases such as figshare (Dwyer *et al.* 2015, Wikelski and Kays 2017). The major benefit of radio telemetry is its ability to provide detailed datasets for wildlife conservation and management (Kays *et al.* 2015). By ensuring that radio telemetry studies are used to their full potential, we can provide land managers and biologist with the information they need to ensure the survival of desert species.

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Figure 1(on next page)

PRISMA Flow Diagram

PRISMA Flow Diagram for the identification of studies included in this review.

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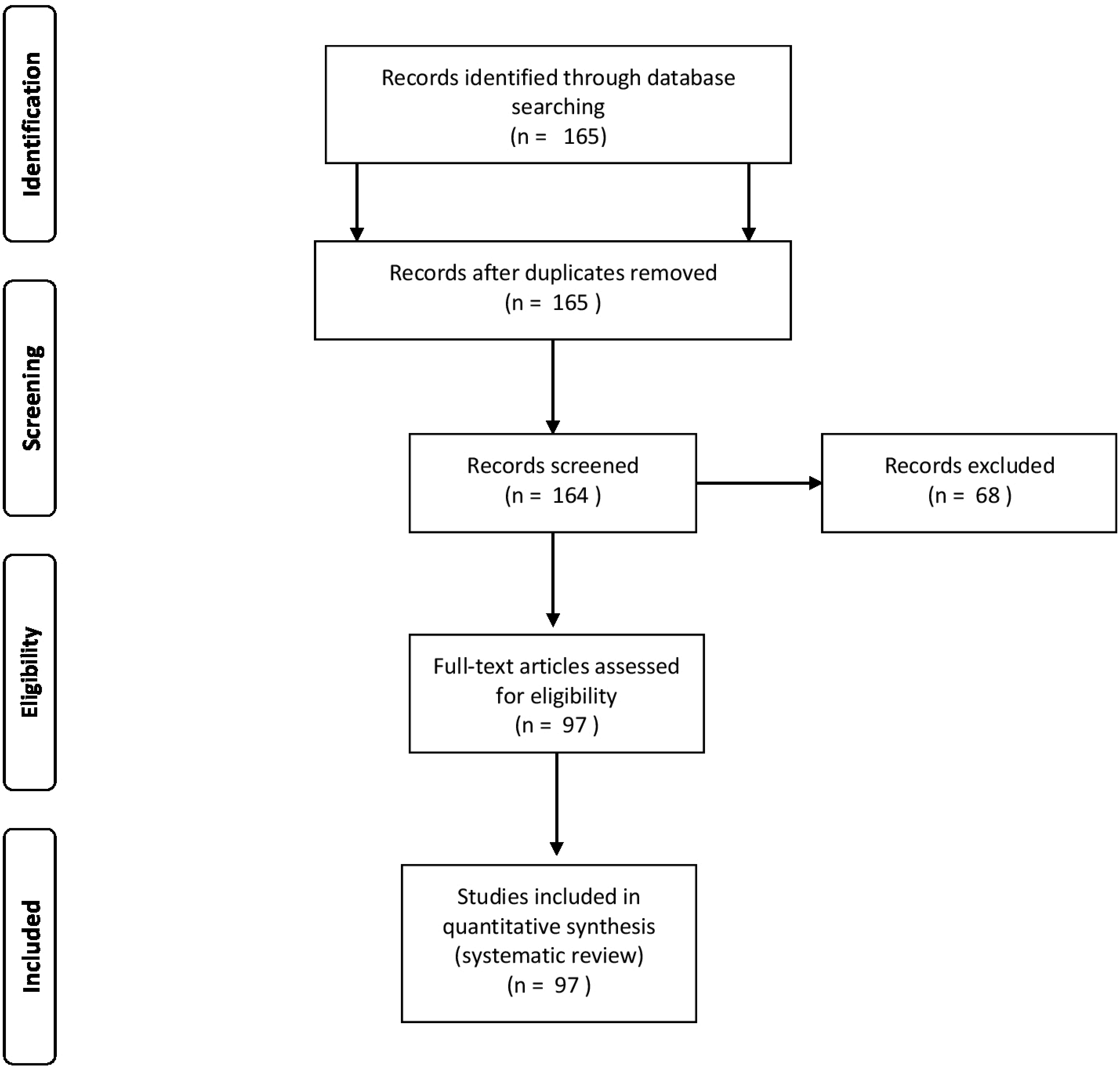


From: Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group (2009). *P*referred *R*eporting *I*tems for *S*ystematic Reviews and *M*eta-*A*nalyses: The PRISMA Statement. PLoS Med 6(6): e1000097. doi:10.1371/journal.pmed1000097

For more information, visit www.prisma-statement.org.

Figure 2

(on next page)

Map of study sites

A map of the world showing the global distribution of studies examined in this review. The largest proportion of studies were in the United States (36 %, n = 35), Australia (16.5 %, n = 16), and South Africa (7.2 %, n = 7).

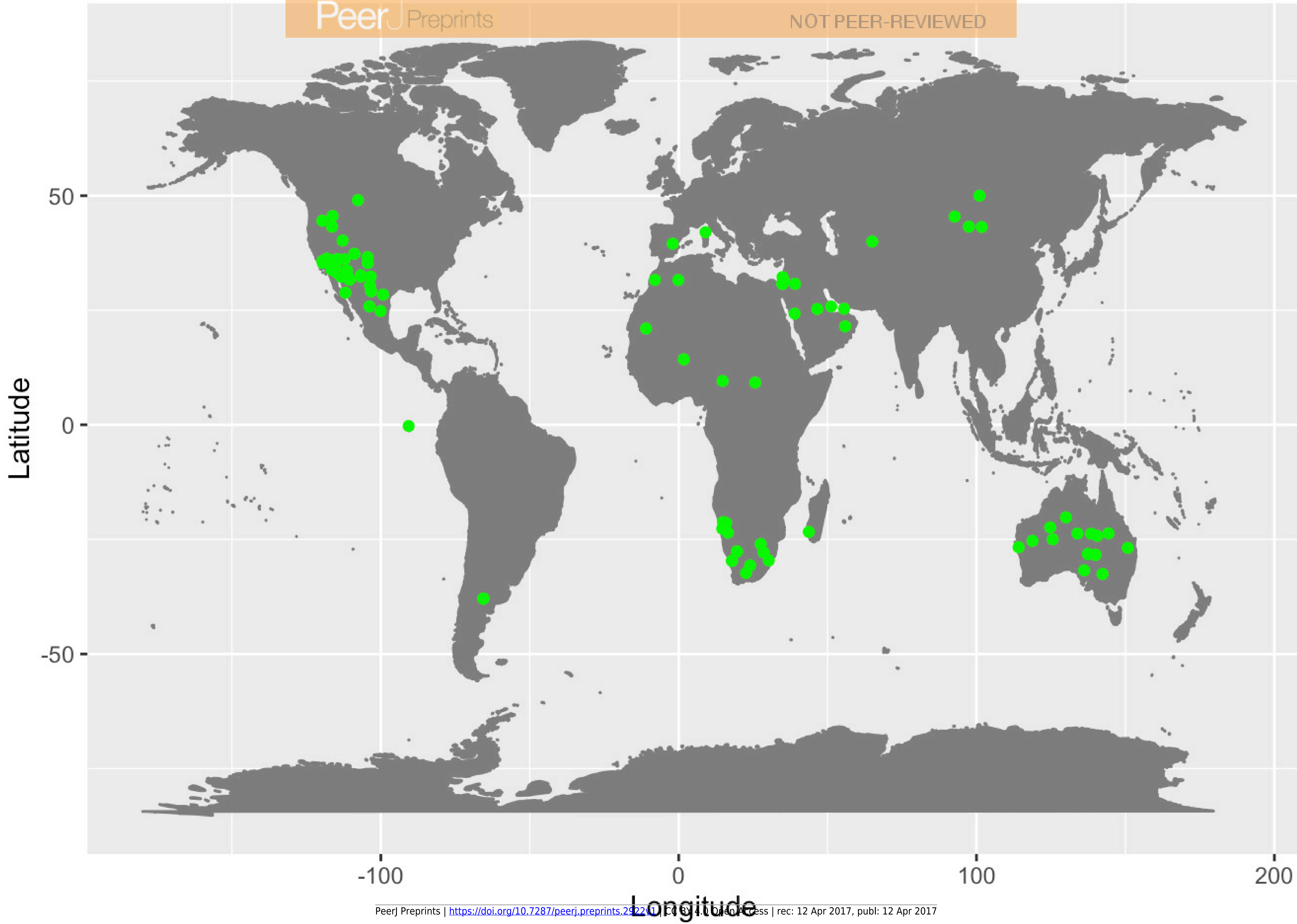

Latitude
50
0
-50
-100
0
100
200
Longitude

Figure 3 (on next page)

Frequency of Ecological Purpose

The frequency of each ecological purpose examined with the frequency of taxa studied in each. The main ecological purpose of these studies were behavior and habitat use with 39.2 % and 37.1 % respectively. The most common classes of animal studied were large and small mammals (29.9 % and 25.8 % respectively), followed by birds (21.6 %) and reptiles (20.6 %).

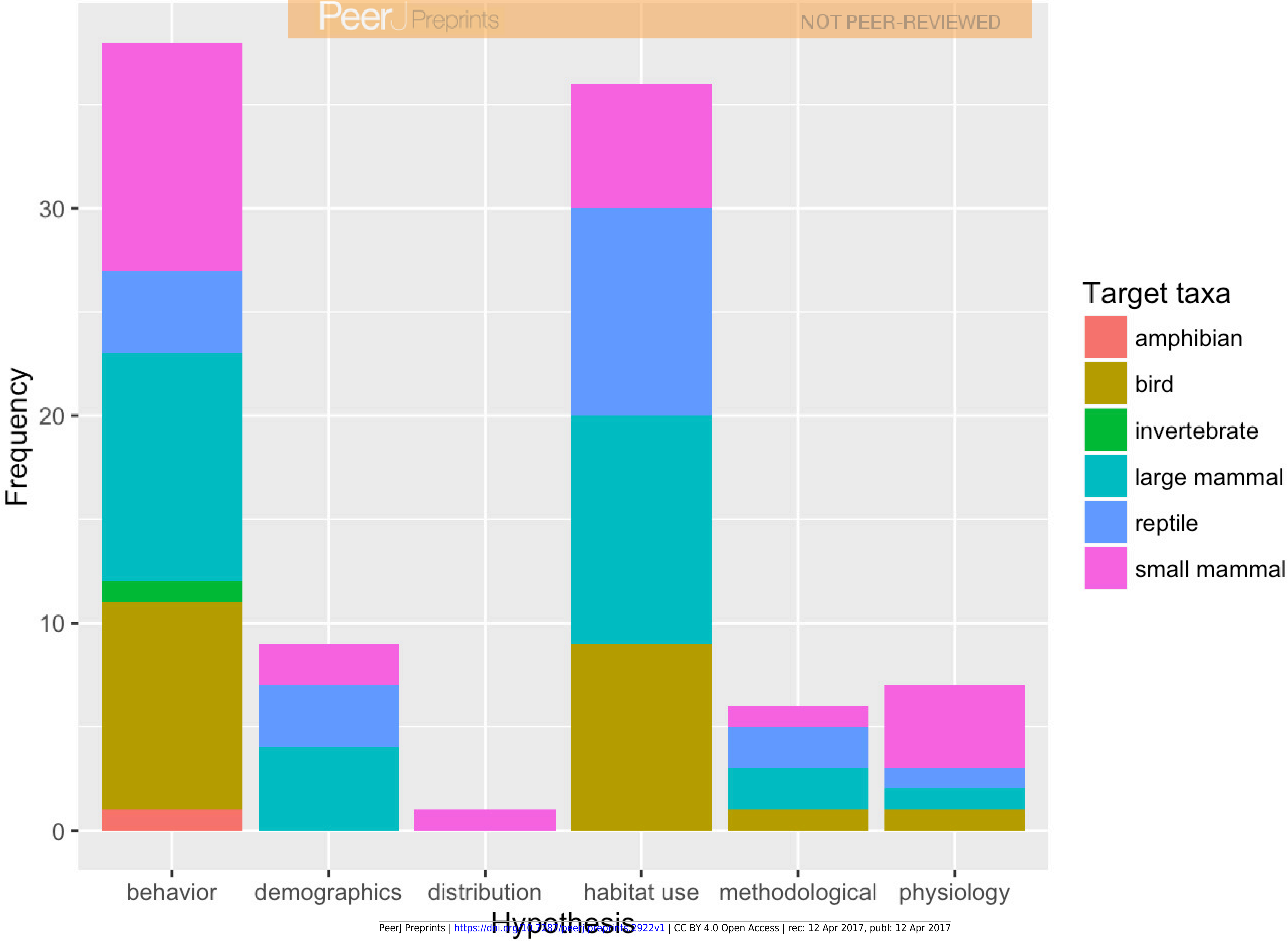
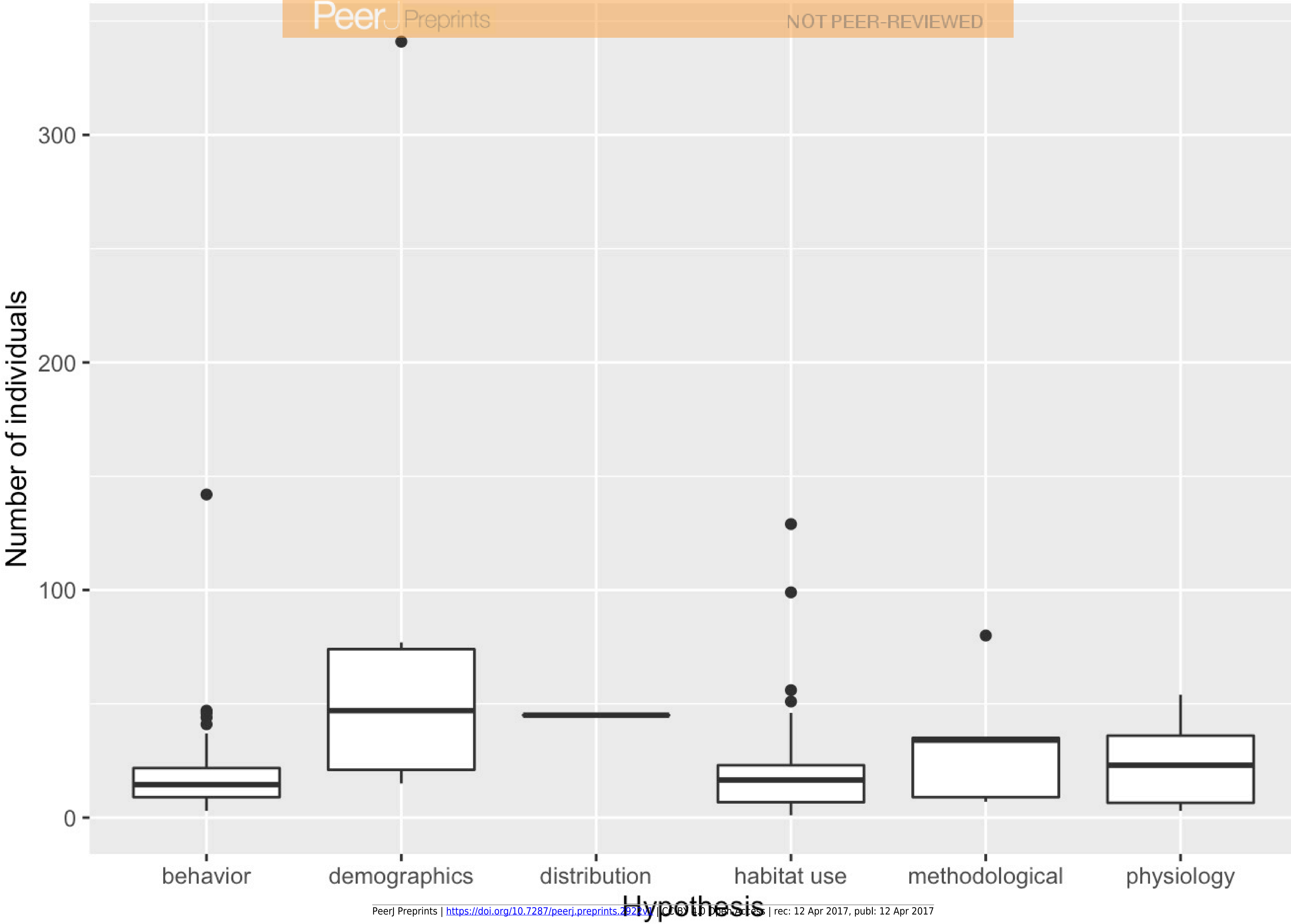

Frequency
0
10
20
30
behavior
demographics
distribution
habitat use
methodological
physiology
Hypothesis
Target taxa
amphibian
bird
invertebrate
large mammal
reptile
small mammal

Figure 4(on next page)

Sample size by frequency

The frequency of each ecological purpose examined with the frequency of sample size by ecological purpose studied. Hypotheses examining demographics and distribution had a higher mean sample sizes.

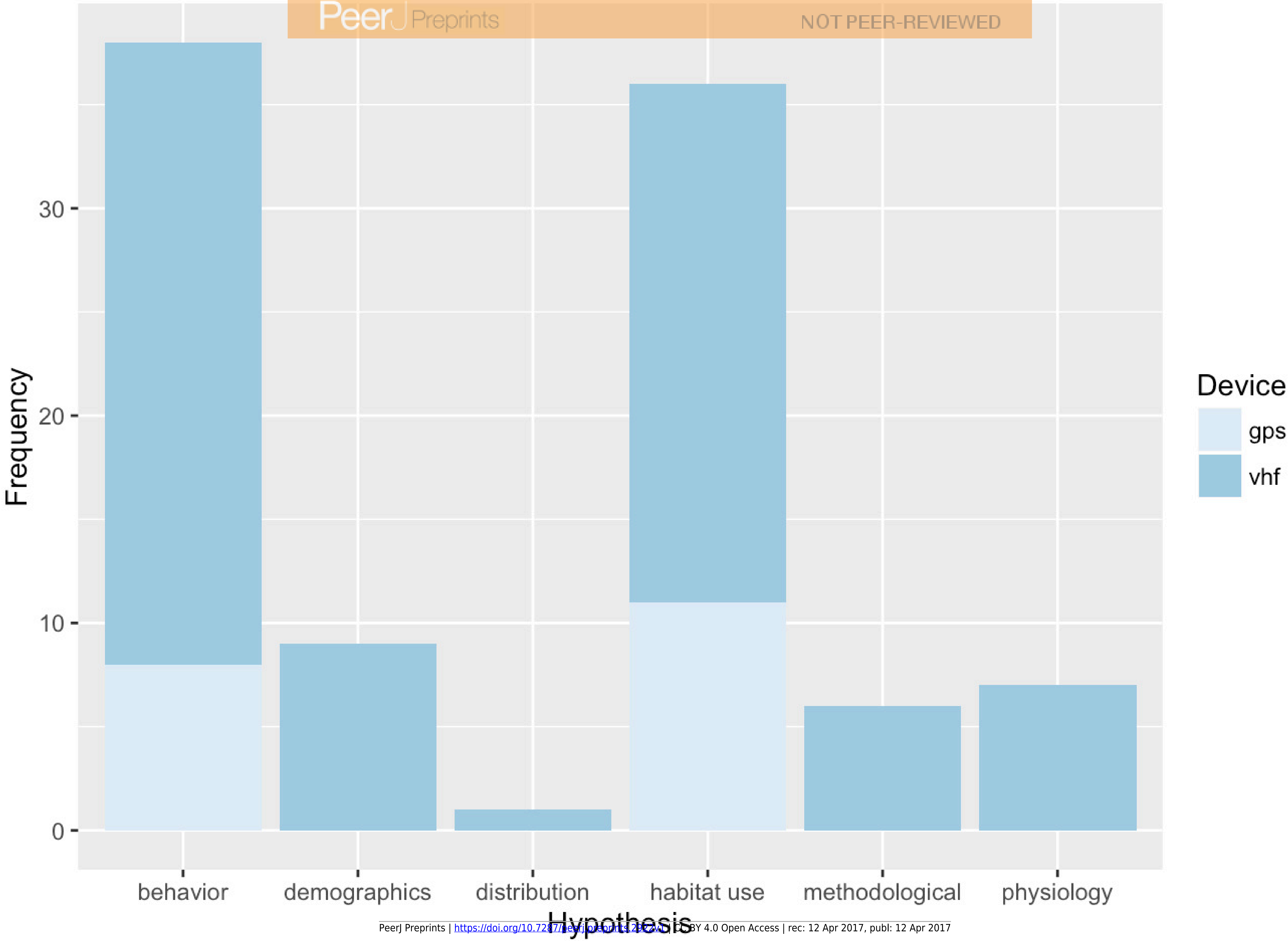


Number of individuals
300
200
100
0
behavior
demographics
distribution
habitat use
methodological
physiology
Hypothesis

Figure 5(on next page)

Frequency of ecological purpose by telemetry device.

Frequency ecological purpose studied with frequency of radio telemetry device used. Most studies utilized vhf radio telemetry devices (80.4 %). GPS devices were used in 19.6 % of studies (n = 19). The GPS devices were used exclusively in studies that examined behavior and habitat use.



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