# Minimum reporting standards can promote animal welfare and data quality in biologging research

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## Abstract

Biologging best practices have been carefully considered since the field's inception six decades ago. The biologging research community has reduced instrument impacts on study animals by miniaturizing devices, employing sophisticated release mechanisms, and developing novel technological advancements. However, the field still needs standardized best practices for balancing data quality and animal welfare across the scientific process, from design to deployment to reporting. We developed a set of guidelines by reviewing over 150 recent biologging impact studies for instrument characteristics and effects on animal physiology, behavior, and/or demography. From these studies, we distilled eight best practices that can be used by biologging researchers, with a particular focus on minimum reporting standards as a low-cost, high-impact way to promote animal welfare and data quality. We present three scenarios to demonstrate how reporting instrument, data, and animal characteristics can reduce instrument impacts, support future meta-analyses, and facilitate interdisciplinary collaborations. Finally, we summarize the state of knowledge surrounding the impacts of biologging instruments to animals and data. Adopting standardized guidelines for instrumentation best practices is a crucial step towards ensuring that future biologging efforts minimize impacts on animal physiology, behavior, and demography - the very biological metrics our instruments are meant to measure.

## 1. Introduction

Discoveries in ecology, physiology, and animal behavior increasingly come from instrumented animals that collect *in-situ* environmental and biological data [1–4]. Modern instruments can be small enough to attach to insects [5] or implant in goldfish [6], cheap enough for large sample sizes [7], and sophisticated enough to concurrently measure animal decisions and environmental conditions [8]. This "golden age" of biologging has allowed us to collect ecological data at an entirely new scale [4,9], from individuals in a single location at a specific time of year to ecosystem-wide monitoring across seasons and continents [10]. As biologgers inform both basic and applied science through research across disciplines, many researchers are seeking guidelines for best practices of similar breadth.

Biologging best practices have been discussed since the field's inception more than six decades ago [11–15]. Since then, technological advances have occurred more rapidly than researchers and regulatory agencies can adjust their standards, resulting in arbitrary "rules of thumb". The '3% rule', for example, suggests that instruments should weigh less than 3% of the study animal's body mass [16]. However, several recent studies have emphasized the subjective nature of the rule [17–20]. Additionally, while the miniaturization of bio-loggers has resulted in smaller instruments on animals, it has also led to the instrumentation of increasingly smaller animals [21], necessitating further conversations about instrument impacts.

Novel, fundable, impactful science often demands larger sample sizes, increased sampling across demographic groups, smaller study species, longer study durations, and more data streams, all of which require more from the animals that carry the instruments. However, the acceleration of biologging science has far outpaced the development of reporting guidelines. As biologging efforts grow, the ad-hoc reporting of instrument impacts will be insufficient to ensure animal welfare and scientific rigor [22,23]. The biggest challenge in realizing these best practices is not a lack of rigor, technological ability, or concern for the animals, but rather the lack of essential infrastructure such as a minimum reporting standard. Minimum reporting standards for data, often presented as a table or checklist, are common in other scientific disciplines to promote data transparency, reproducibility, and utility [24–27]. Biologging researchers have called for some types of minimum reporting standards in the past, particularly for instruments that record animal location [12,23,28–31]. As biologging instruments become less expensive and more accessible, researchers, journals, and funders are better positioned than ever to implement these standards.

Here, we propose best practices for biologging researchers from development to deployment to reporting based on more than 150 recent biologging studies. We offer three scenarios following biologging researchers across disciplines and study species to ground these practices in reality, emphasizing reporting as a prime opportunity for low-risk, inexpensive, and impactful interventions. Finally, we summarize the existing literature on biologging instrument impacts to emphasize research gaps and provide context for our proposed minimum reporting standards for instrument characteristics. Robust biologging infrastructure, including reporting standards, will facilitate the expansion of biologging across the globe and across disciplines while preserving animal partnerships and data quality.

## 2. Recommendations for biologging best practices

Based on a review of the physiological, behavioral, and demographic impacts of biologging instruments on animals, we created a checklist of best practices across the stages of biologging research (detailed below, in Figure 1, and in Table S1).

### 2a. Establish partnerships during the design phase.

Partnerships between instrument manufacturers and researchers can facilitate the development of low-impact instruments [31]. Researchers can provide expertise on which characteristics are important in their study system (e.g., hydrodynamic shape, species-specific attachment, flexible battery size, remote release, etc). Instrument manufacturers can use their engineering and design expertise to make feasible adjustments. Researchers and engineers can use computational modeling to test new sensors [32], calculate impacts [33], and optimize designs and positions [34,35].

2b. Carefully choose sample sizes.

Selecting a sample size is a crucial part of biologging study planning [7,36]. While some experimental biologging studies are limited in sample size due to the expense of instruments, researchers using off-the-shelf instruments may be able to reduce their sample sizes depending on the scale of their ecological question. Ensuring appropriately small sample sizes conserves resources and reduces the number of individuals that may experience negative impacts from instruments [13].

2c. Use un-instrumented control groups.

Biologging studies should compare instrumented and non-instrumented animals whenever possible. Studies that compare instrumented versus non-instrumented physiology (e.g., body condition or stress hormones), behavior (e.g., foraging trip duration), and demography (e.g., reproductive success or survival) play a critical role in our understanding of tag impacts and confidence in the quality of biologging data. While not always possible, this practice can help detect instrument impacts and assure that biologging findings are generalizable to the larger population [37].

2d. Assess potential impacts on animals in managed care.

Testing the impacts of devices on animals housed in human care (e.g. zoos, aquaria, or other research facilities) affords researchers the opportunity to quantify physiological and behavioral impacts relative to instrument characteristics and attachment methods. While animals in managed care may not behave exactly like their wild counterparts, testing for short-term impacts may direct researchers towards small, but critical, adjustments that can greatly improve welfare during deployments on wild animals.

2e. Monitor studies regularly for signs of impacts.

Researchers should pay close attention to signs of physiological, behavioral, or demographic impacts and be ready to change protocols during the study to minimize or reduce impacts. Small changes such as attachment method (e.g., amount of glue used) and location (e.g., a few inches forward or backward) can result in large improvements for animal welfare [38,39].

### 2f. Report null impact results.

Publications that report negative impacts are much more common than those that report null impacts, at least in part because of the difficulty of publishing null results [26]. Null impacts should be reported whenever possible, whether as a part of a larger biologging study or separately. Null impacts should be determined through rigorous data collection instead of being assumed from anecdotal or observational evidence alone. Assessments and reports of statistical power can help to ensure that results from individual studies are not overstated [40]. Furthermore, concerted community efforts to bring vast amounts of unpublished knowledge into the published literature (e.g., [41,42]) would greatly benefit the biologging field.

### 2g. Minimize deployments by maximizing data reuse.

Embracing open data and reproducibility will accelerate the pace of discovery in biologging data [43], ultimately allowing researchers to save time and money, reduce the impacts to animals, and continue to publish cutting-edge science. Although many biologging studies are published in journals with clear data accessibility requirements, many ecological studies archive incomplete datasets that are insufficient to reproduce the analysis or reuse data. Unlike fields such as genomics, biologging does not yet have a central data repository or standardization practice [23,28,29]. Data-driven questions and global collaborations can enable researchers to reuse or re-analyze data for new discoveries [10,31,44,45], reducing the number of animals that experience the impacts of carrying an instrument.

### 2h. Utilize minimum reporting standards in manuscripts.

All biologging studies could include descriptions of instruments and attachment methods [23]. Using generalizations from the known impacts across taxa, we collated a list of instrument characteristics for consideration throughout the process of instrument development, deployment, and data dissemination. The minimum reported characteristics should include the instrument type, placement, weight, size, material, cross-sectional shape, manufacturer and model number, attachment and detachment method, deployment duration, sensor list, signal production, and the intensity and frequency of signals (Figure 1; Table S1). Reporting relative characteristics, such as the ratio between instrument/animal body mass or the ratio between instrument/animal cross-sectional shape, can help to evaluate, update, and develop “rules of thumb” that can be useful when developing new tags and instrumenting new species.

## 3. Scenarios

Here, we present three hypothetical scenarios to describe realistic implementation of best practices in biologging. These scenarios cover different research phases, from initial **design** of studies and instruments, through instrument **deployment** and data collection, to **reporting** results and sharing data in publications.

### 3a. Scenario**:** Adapting a biologger for a new species

*Design:* A researcher leading a long-term study at a cormorant colony wants to use a video biologger to investigate social cues and foraging behavior. They contact a biologging manufacturer that makes similar tags for terrestrial birds, who agrees to **collaboratively** adapt the instrument for a diving bird. Working together, they identify potential risks and mitigation measures based on meta-analyses of instrument impacts to birds that fly and swim. Their instrument prototype is lightweight and uses a streamlined profile to minimize drag in air and water. In their first deployment season, the researcher decides to **instrument the minimum number** of birds that will still provide sufficient data to explore within-colony variation in foraging strategies. Careful choice of **sample size** ensures that animals will not be unnecessarily instrumented.

*Deployment*: The researcher deploys the new instruments and instructs field technicians to observe and report on the welfare of the instrumented animals. Although the principal purpose of these initial deployments is not to comprehensively assess instrument impacts, they take advantage of ongoing monitoring efforts to select a **control group** of uninstrumented birds for comparison of chick provisioning rates. At the end of the deployments, they found that instrumented birds on average fed their chicks 10% less often than the control group, though still within normal behavioral variability for the population. Out of an abundance of caution, they **adjust their protocol** to reduce the video duty cycle for the following season, which will allow them to reduce the battery size and overall weight of the instrument.

*Reporting*: At the end of two field seasons, the researcher analyzes the video data and writes a manuscript about their findings. In their supplementary materials, they **document instrument details** including dimensions, weight, material, and manufacturer. They report the initial decrease in chick provisioning rates in the first set of deployments and how they addressed it by reducing the instrument’s weight. They **publish their data** in an open repository, which will allow other researchers to explore the videos and inform their decisions to deploy video biologgers on other species.

3b. Scenario: Deploying an off-the-shelf biologger

*Development*: A postdoc joins a lab to deploy biologging collars on juvenile coyotes, intending to measure their scent marking behavior via accelerometers. Most of the lab’s previous work has been on mountain lions, so the postdoc carefully **reviews the existing literature** to choose an appropriate collar and consider the potential impacts. While they don’t find any published meta-analyses of the demographic impacts of collars, they found a few government reports (**gray literature**) indicating potential issues with juvenile instrumentation, particularly issues with sizing as the animal grows. They use this information to carefully **choose an instrument** that is expandable and will be snug enough to prevent foreign objects from entering the collar, but loose enough that the collar will still fit as the animal grows. They also opt for a GPS/accelerometry capable weak-link collar, which allows the collar to release after a set period of time.

*Deployment*: While they aren’t able to study animals in managed care or follow uninstrumented animals as a control, the postdoc decides to **deploy a small number of tags** and assess the results before deploying their full sample. When there are no apparent issues, the postdoc puts out the rest of the collars.

*Reporting*: After a few weeks, the postdoc retrieves the collars, downloads the data, and drafts their manuscript. In their methods section, they include the **make and model** of the collar they used, with a link to the manufacturer's website. Their research is well-received, and colleagues at a conference suggest that they analyze GPS in addition to accelerometry data. Instead of deploying more collars, the postdoc decides to **re-analyze** the original unused GPS data to answer these new questions. They publish their dataset in a data repository and make their code publicly available to help future grad students in the lab.

### 3c. Scenario: Developing a novel instrument

*Development:* A graduate student is interested in instrumenting seven-gill sharks with a novel biologger with many sensors, including conductivity, temperature, pressure, dissolved oxygen, and passive acoustics. They **collaborate** with engineers at a partner institution to design, build, and test the instrument. Although a statistical power analysis was used to inform their **sample size** goal of 20 biologger deployments, they wrote several pilot projects into their research grant. First, the student tests the instrument in a **flow tank** to make sure the design is as streamlined as possible and to make sure the instrument records usable data. The number of sensors necessitates a relatively large instrument size as well as a significant electrical field, which the student thinks may disrupt the behavior of a shark that relies on magnetic fields for sensation. They therefore **partner with a local aquarium** that houses seven-gill sharks. They temporarily attach the biologger to a shark and monitor its time activity budgets from surveillance video to ensure that behavior is no different when the biologger is attached.

*Deployment*: The student deploys instruments on a small number of wild sharks to ensure that foraging and diving behaviors match the typical patterns from **control sharks** in the aquarium. When the instruments are successfully returned with usable data and no evidence of behavioral disruption, they deploy their full sample size.

*Reporting*: At the end of the field project, the student writes a manuscript that includes **detailed information** about instrument design elements and **null impact results** from both the aquarium study and control group comparison. They **publish** all the streams of their data in an open-access journal to inform policy decisions about elasmobranch conservation.

## The need for standardized best practices across the scientific process

The solutions described above are broadly applicable regardless of the unique challenges of each discipline and study system. The strength of these best practices lies in their spanning the scientific process, from design to deployment to reporting. It is unreasonable to expect every study to evaluate every potential instrument impact. Each of the researchers in our scenarios implemented the best practices to their fullest ability, taking into account the structural, logistic, and financial barriers they faced. However, a single solution that would support all three researchers is a minimum reporting standard for data, animal, and device characteristics. In addition to helping with future meta-analyses and syntheses, these guidelines can also facilitate efforts to refine development and deployment strategies in future research endeavors. Adopting a minimum reporting standard is a low-risk, high-reward next step for quantifying and minimizing instrument impacts.

## 4. Considerations across disciplines and taxa

Understanding previous impact studies is one of the most informative tools for designing and deploying biologging instruments. While many impact studies exist, they are typically taxa- or method-specific. Here, we synthesize >150 recent novel biologging studies and impact studies to generalize across transport modalities (walking, swimming, and flying animals) and research disciplines (physiology, behavior, and demography). This review and synthesis directly informed the development of the best practices detailed above. Details of individual studies are available in the Supplemental material (Table S2).

Instruments may impact the animals that carry them at multiple biological scales, including their physiology, behavior, and demography (Table 1). These effects are largely influenced by the interaction of instrument attachment/type with the animal's transport modality. In a hypothetical example, a tail-mounted GPS tag (*instrument* *attachment/type*) attached to a swimming + flying bird (*transport modality*) may increase the metabolic costs of flight (*physiological impact*), which is associated with shorter foraging trips (*behavioral impact*) but does not affect chick growth rates (*lack of demographic impact*). It is important to note that while demography may not be affected in this example, physiological or behavioral adjustments may compromise the "natural" data collected by the instruments. Due to resource and logistical limitations, most studies can only feasibly report impacts at one biological scale if impacts can be quantified at all. The relative importance of impacts and availability of solutions varies widely within and across transport modalities and taxa, particularly for species that use multiple transport modalities (Figure 2). Transport modalities, instrument and attachment types, and other relevant terms are defined in the Glossary.

## 4a. Impacts to Walkers

Terrestrial environments host a wide range of walking specialists that must contend with high environmental heterogeneity, climate variability, and physical obstacles. The instruments most frequently affixed to walking specialists are biologging collars such as GPS collars, which can cause injuries to the animal's neck due to chafing [46–48]. Collars must be sized appropriately to minimize interactions with the environment during movement and growth and prevent debris, such as twigs, from becoming lodged in the collars [47]. Collars that expand as animals grow are a helpful tool for avoiding injuries when instrumenting juvenile walkers [49].

In addition to heterogeneity in physical features, terrestrial environments also have variable climates, and changes in precipitation or temperature can alter the impacts of biologging devices on the animals that carry them. For example, in heavy-rainfall areas, the tape used to attach instruments to the tails of greater bilbies (*Macrotis lagotis*) occasionally became saturated and compacted with mud, causing skin injuries [39]. For walking ectotherms, healing rates are affected by temperature-dependent metabolic rates, which can disrupt recovery from surgery or other instrument-derived injuries [50]. Physiological impacts to walkers are often attributed to disruption of fur or feathers, leading to compromised thermoregulation and therefore elevated energy expenditure [51] or reduced body condition [52].

Impacts to walking species are most often assessed at the scale of behavior, and several studies have found significant behavioral changes among instrumented walking specialists. For example, a GPS collar weighing 1.8 kg reduced walking speed of zebras (*Equus burchelli*) while foraging by >50% relative to a collar weighing 1.2 kg [53]. Both collars weighed substantially less than 3% of the animal's body mass, acceptable under the traditional "rule of thumb." These results raise concerns not only about impacts to animal well-being, but also to data quality. Additionally, the attachment methods and instrument placement appropriate for a slow-moving herbivore are very different from those appropriate for a high-speed carnivore. Instruments, especially GPS collars that are not flush with the skin, can affect the acceleration of athletic animals that rely on running speed to catch prey or escape predation [54]. In some athletic walking species, the forces exerted by instruments weighing less than 3% of the animal's body weight created much larger inertial forces when the animal was moving at speed [54]. For the fastest species, carrying these small instruments at top speeds was the equivalent of carrying a device weighing up to 19% of the animal's body mass [54]. These findings informed our decision to include detailed instrument and animal characteristics in our minimum reporting checklist, including instrument dimensions and weight in air (Figure 1, Table S1). The behavioral impacts of biologgers on extremely athletic walking specialists is an important data gap, particularly for taxa that rely on behaviors close to their physiological limits.

In summary, researchers instrumenting walking species are required to consider environmental heterogeneity, climate variability, and physical obstacles. When possible, continuous monitoring is helpful for assessing whether these factors will negatively impact the animals and the data. Additionally, despite the unique constraints associated with biologging collars, there appear to be few meta-analyses available to address their impacts. A minimum reporting standard for animal, data, and instrument characteristics would help to fill this knowledge gap.

4b. Impacts to Swimmers.

In high-drag aquatic environments, minimizing mass and maximizing streamlining are both important to reduce instrumentation impacts [55]. Researchers instrumenting aquatic species employ a diversity of attachment methods, including suction cups for cetaceans, glue for pinnipeds, tape for seabirds, subdermal attachment for turtles and sharks, and implants for fish. Some attachment methods, particularly harnesses and collars, have negatively impacted animal survival in the past [56]. Because the impacts of these methods were published, the field has largely been able to move towards lower-impact methods [57–61].

The physiological impacts of instrumentation on swimmers include changes in energy budgets, thermoregulatory processes, and body condition. Endothermic aquatic species often rely on blubber, fur, or feathers for insulation in a thermally conductive environment [62]. Devices can exacerbate thermoregulatory requirements by disrupting their insulation [63]. Instrumentation may impact species that rely on fur or feathers [52,64] more than species that rely on blubber or other thermoregulatory adaptations [58,60,65,66]. For example, cutting pelage to remove glued instruments from northern fur seals (*Callorhinus ursinus*) significantly decreased the thermal resistance in the area around the cut fur; however, utilizing a neoprene patch for attachment effectively mitigated the negative thermoregulatory effects [63]. The potential for thermoregulatory impacts is one reason we included reporting of attachment method and location in the minimum reporting standard for instrument characteristics (Figure 1, Table S1).

Instrumentation injuries on swimming animals are usually minor. Glued and suction-attached devices may cause minor irritation, but significant injuries are rare. Subdermal attachments, such as instruments attached by screws to a shark’s dorsal fin, can cause permanent cosmetic damage; however, this damage does not seem to impact growth or survival [67]. Attachment injuries may be relatively infrequent in swimmers because instruments are often placed flush to the skin to reduce drag, reducing opportunities for chafing, fouling, and entanglement.

Biologging can allow for otherwise challenging underwater behavioral observations [68], but control data are needed to ensure that instruments capture normal animal behavior. Biologging devices attached externally to swimmers increase drag forces, which can increase metabolic rate [69], cost of transport [70], and power consumption [71]. Some swimmers change their behavior to compensate for physiological impacts, such as reducing swim speed to compensate for increased locomotor costs [72]. Compensation may even happen across individuals, as in cases where un-instrumented parents increase offspring provisioning to compensate for an instrumented partner's reduced contributions [73]. The instrument characteristics that are most likely to contribute to drag include attachment method (i.e., harness vs. glue) and cross-sectional shape (streamlined vs. complex) [34,55,74–76]. While attachment methods are frequently reported in manuscripts, cross-sectional areas are not, likely because they can be difficult to calculate. We nonetheless recommend reporting cross-sectional areas whenever possible, particularly for swimming species. The potential impacts of drag are frequently studied in collaboration with researchers who can facilitate impact studies through captive animal trials and/or computer modeling, both of which are excellent options to explore prior to instrumentation on wild animals.

A swimmer's buoyancy may change as they dive, become pregnant, or gain/lose weight over the course of a migration [77]. Instrumentation can affect buoyancy, resulting in behavioral and physiological changes [20,78]. For example, northern elephant seals (*Mirounga angustirostris*) carrying experimental buoyancy blocks adjusted their swimming stroke rate to maintain their swim speed [79]. Biologging devices - intended to record non-biased physiological or behavioral data - should be neutrally buoyant when possible, particularly for long deployments. We therefore included buoyancy as a part of the instrument characteristics reporting standard for biologging studies involving swimmers (Figure 1, Table S1).

The potential for instruments to increase predation risk via reduced mobility or signal production has been hypothesized, but not substantiated. Many instruments produce signals such as light or sound that may attract predators. For example, predation rates on instrumented eels (*Anguilla rostrata*) were extremely high (75%), but it is unclear whether these mortality rates were higher than un-instrumented counterparts [80]. Sharks in particular forage by detecting the weak electromagnetic fields of their prey [81] and have been known to ingest instrumented prey [82]. Nonetheless, it remains an open question if carrying electronic instruments significantly increases the risk of mortality for swimming prey species. Including signal production in the minimum instrument characteristics reporting standard could help answer this question in the future.

In summary, researchers instrumenting swimming animals must consider several unique constraints, including the increased drag, density, and heat capacity of water. Because it is rare to validate swimmers' biologging data with visual observation, robust reporting of instrument characteristics and resulting meta-analyses may be the main avenue for discovering impacts to animals and data quality.

4c. Impacts to Flyers.

Instrumented flyers, including bats, birds, and insects, typically have smaller body sizes than walkers or swimmers and are often instrumented with backpacks, harnesses, implants, or trailing attachments [2,3]. Bats and walking birds such as grouse are frequently collared. For very small animals such as insects, miniature instruments are usually glued to the animal's back. While there is a rich literature associated with the impacts of instrumentation on birds, the impacts to other flyers, especially invertebrates, are less well known [83,84]. These major meta-analyses have been possible in large part due to the reporting of instrument characteristics such as weight in avian biologging manuscripts, which is less common in other taxa.

Powered flight carries the highest metabolic demands of any locomotor mode [85]. When instrumentation adds to these already considerable costs, there can be substantial impacts to daily energy expenditure and mass balance [17,18,86–90]. For example, instrumented homing pigeons lost an amount of body mass equivalent to the mass of the instrument they carried [89]. The recommended limit for instrument mass is

3% of the animal's body mass; however, physiological impacts have been documented for smaller instruments as well [17].

Although instrumentation best practices for avian flyers are well-established, instrumentation can nonetheless result in unexpected injuries. For example, heat from instruments attached to the upper backs of ibises (*Geronticus eremita*) caused corneal opacity because of the birds' roosting posture [38]. In this case, careful monitoring during the study and a small shift in attachment location prevented damage in subsequent deployments. Device implantation carries additional risks because it requires a surgical procedure. However, once implanted, these instruments cause fewer negative impacts than external devices [91]. External tags on flyers share swimmers' difficulties regarding drag [92], and collared flyers (typically bats) face the same issues with chafing and entanglement as collared walkers [93].

The potential for negative physiological impacts can increase with the duration of instrument deployment. Instrumented murre species (*Uria aalge* and *Uria lomvia*), had higher levels of corticosterone after year-long instrument deployments, while short-term deployments had no effect on corticosterone levels [94]. Researchers should carefully consider and report the deployment duration when designing a study, particularly if the deployment period will overlap with multiple major life events such as breeding, molting, or migrating (Figure 1, Table S1).

Some flying animals change their behavior to compensate for physiological or demographic impacts. Instruments can reduce the amount of time spent flying [95,96], reduce flight speeds [97], and disrupt chick provisioning behaviors [90,98]. Additionally, many of the most commonly instrumented flying specialists undergo long migrations and carry their instruments across entire oceans [5,88,99]. Instrument weight and shape, among other characteristics, are critical to report, as they could cause changes in flight behavior, migration distances, and survival. Attachment is also important: backpack attachments have been shown to alter flying behavior more than leg loop attachments, likely because of increased drag [100]. These behavioral adjustments may allow species to compensate for instrumentation without altering reproductive behaviors such as chick provisioning [64,101]. Further study is necessary to determine when changes in behavior (or lack of compensatory behavior) may cascade to demographic impacts.

A review of more than 200 studies on instrumented birds found negative effects of instrumentation on survival, reproduction, and parental care [19]. Intergenerational and partner specific effects of device attachment have also been noted in multiple flying species [90,98]. Seabirds, for example, are often monogamous, share parental investment, and live in large colonies where device impacts can affect both the instrumented individual, un-instrumented co-parents, and offspring [96,98,102]. Un-instrumented partners, though not burdened with a physical weight, must compensate for their partner's behavioral changes to buffer effects on offspring [90,98]. Elevated parental investment has been linked to the potential for reduced survival in many bird species, indicating potential downstream consequences for instrumentation [103,104]. Whether or not instruments increase parental investment and affect conspecific partners is an important data gap for non-avian flyers, especially when they exhibit colonial or monogamous behavior, like some bat species. With many global populations of birds, bats, and insects at the highest levels of extinction risk [105,106], understanding and minimizing the impacts of devices on demography are extremely important.

4d. Complexity of instrument impacts

Biologging instruments have many potential impacts across time scales and levels of severity. It is difficult to compare these impacts to each other in the same species, let alone across species from different transport modalities (Figure 3). Additionally, instrumentation may be more disruptive in certain seasons, particularly during seasonal periods of mass change such as migration or molt [46,89,107]. Interannual variation in environmental and ecological conditions may result in differential device impacts across years of high and low productivity, even when instrument characteristics remain the same [108]. The interpretation of impacts is widely variable; a similar impact over a comparable time scale may be considered severe by one study and minor by another

[18]. Intraspecific variation can make impacts even less clear, particularly in studies without control groups or large sample sizes [52]. Device deployments on species that share many traits including their use of multiple transport modalities have produced contrary results [3,60,61,73], illustrating the need for robust reporting even in well-studied systems. Finally, although some studies reported impacts, few explicitly described sample size selection, control groups, pilot studies, impact monitoring strategies, instrument characteristics, or open data strategies (Figure 1). Many of these essential processes happen behind the scenes and are therefore not typically included in the manuscript text or supplementary data. This information is nonetheless critically important to continue building on the existing foundation of biologging knowledge, and efforts to bring it into the published literature through minimum reporting standards could facilitate major breakthroughs in future scientific endeavors.

## 5. Conclusion

One of the major barriers to biologging impact meta-analyses and systematic reviews is that information about instrument impacts is often buried, anecdotal, or unpublished. In other fields, including those with rigorous open science requirements such as genomics, a lack of robust metadata has rendered up to 60% of shared data unusable [109]. One potential solution is the creation of a centralized database of biologger deployments and associated instrument characteristics. This major effort would enable future researchers to perform meta-analyses and identify effects that may not be detectable in individual studies. Such a database would be indispensable for us to build on existing knowledge and encourage communication and collaboration between biologging researchers across taxa, transport modalities, and disciplines. In the meantime, minimum reporting standards are a low-investment, high-reward method for building a most robust biologging infrastructure. Eventually, standardized metadata will allow us to quantitatively refine our best practices and learn from the biologging community's successes and challenges. As the field continues to evolve, we are at a crucial moment of opportunity where we can prioritize both rigorous data collection and the care of the animals that make our groundbreaking research possible.

## Acknowledgments

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## Tables and Figures

*Table 1. Examples of impacts to instrumented animals at different biological scales.*

| Biological Scale | Examples of impacts |
| --- | --- |
| Physiology | Changes in thermoregulation, metabolic or energetic costs, hormone production (i.e., corticosterone), and/or body condition (body mass, growth, injury) |
| Behavior | Changes in locomotion (speed, endurance, ability), grooming, foraging, social behavior, provisioning to young (directly and indirectly), mating, predator alert and escape (crypsis, grouping, attraction), and/or athleticism (running, acceleration) |
| Demography | Changes in fitness (in individuals and populations), survival, recruitment, and breeding success, and/or sex ratio |

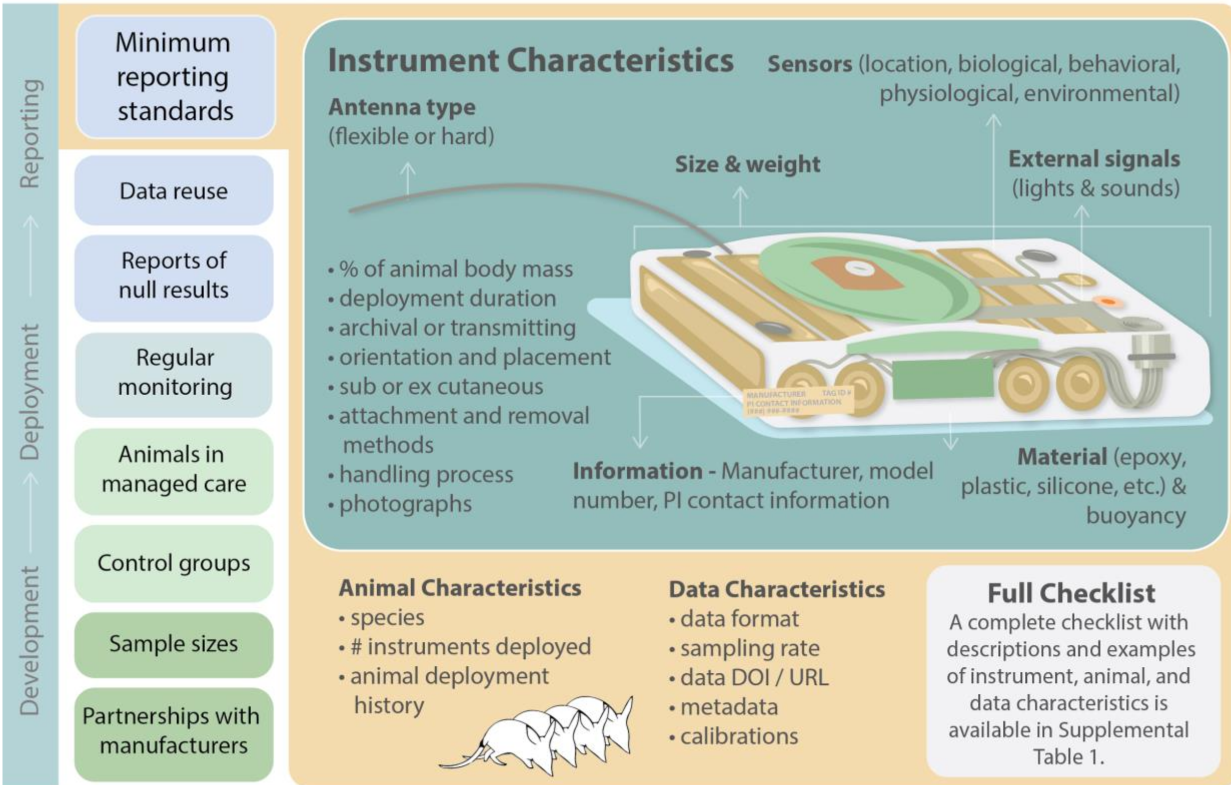


Figure 1. Sample instrument characteristics that would be useful to document and report with biologging manuscripts include size, mass, sensors, orientation, material, cross-sectional shape, and attachment/detachment method. Animal and data characteristics are also helpful to report. For details and examples for all characteristics, see Table S1.

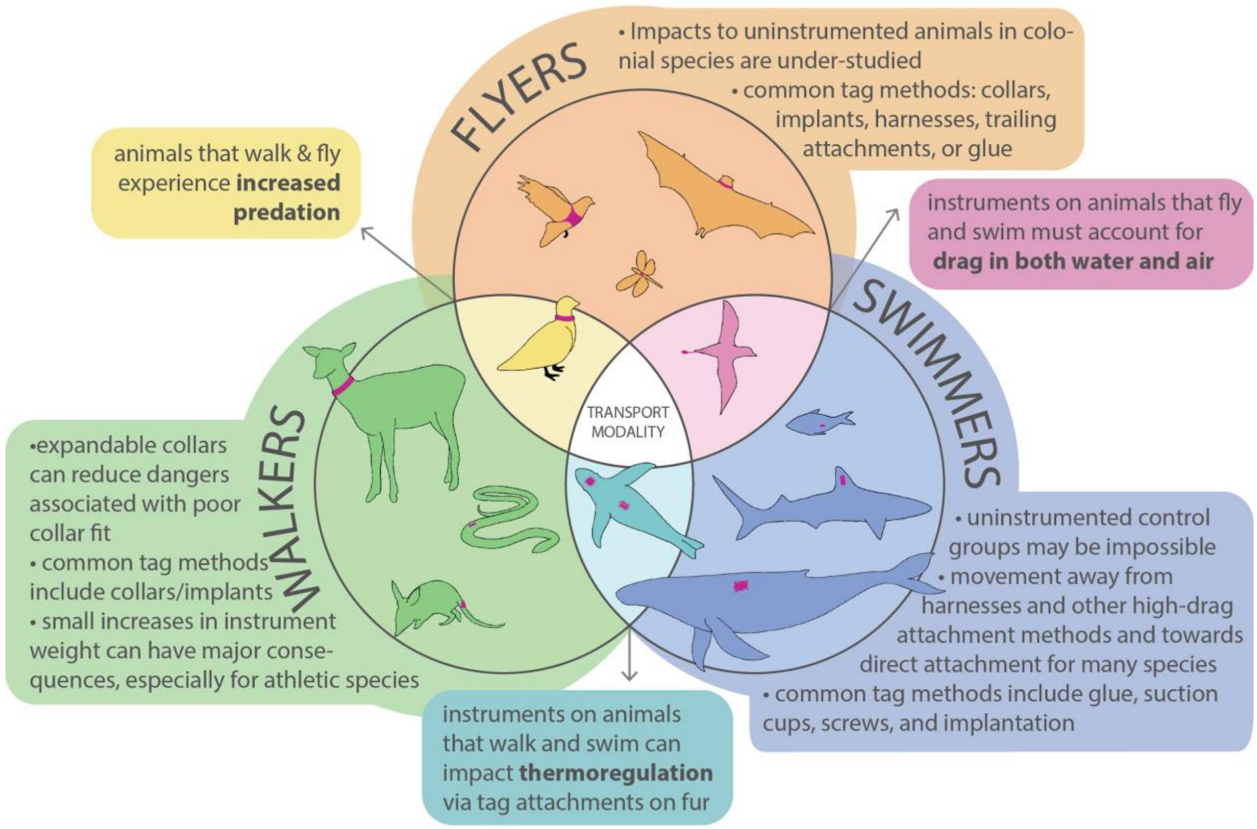


Figure 2. Typical instrument attachment methods and a summary of their associated impacts across walkers, swimmers, flyers, and animals that use multiple modalities.

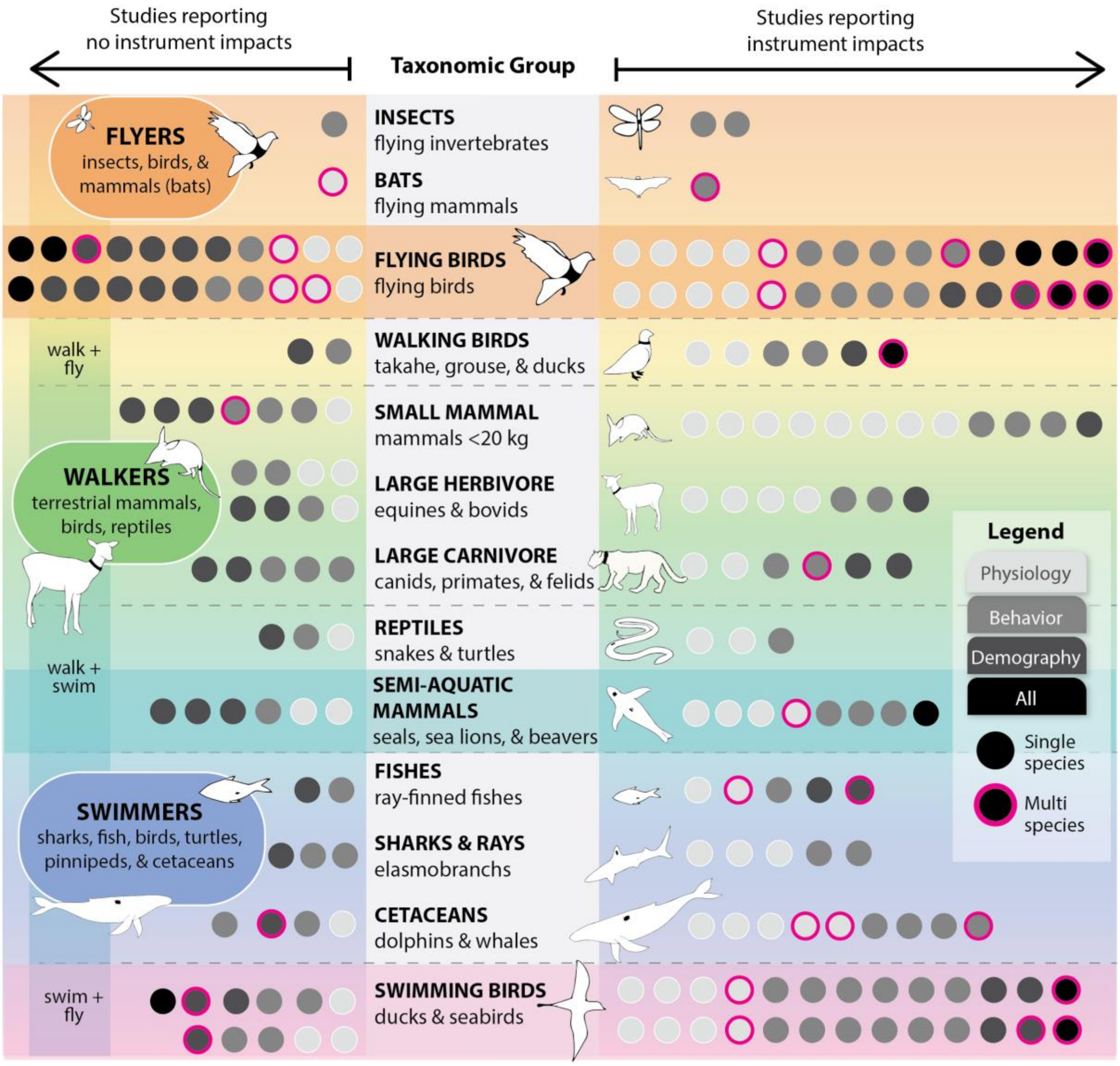


Figure 3. Examples from a comprehensive review of biologging studies that address impacts (or lack thereof) across biological scales and transport modalities. All impacts, even minor ones, are listed under the Impacts section due to the subjectivity of such characterizations. Some studies appear in Impacts and No impacts boxes if their study found both types of results across biological scales. We have focused on papers published in the last twenty-five years due to major differences in best practices prior to the last few decades of biologging research. Information about species, attachment type, and specific instrument impacts is available in Table S2.

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