

COMMENT

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# Towards a minimum reporting standard to promote animal welfare and data quality in biologging research

Allison R. Payne<sup>1\*</sup>, Conner M. Hale<sup>1</sup>, Sarah C. Davidson<sup>2,3</sup>, Jessica M. Kendall-Bar<sup>4</sup> and Roxanne S. Beltran<sup>1</sup>

## Abstract

Over the last six decades, the biologging research community has reduced instrument effects on study animals by miniaturizing devices, employing sophisticated release mechanisms, and developing other novel technological advancements. However, biologging devices can still impact animal physiology, behavior, and demography—the very biological metrics the instruments are meant to measure. Recent meta-analyses have emphasized the subjectivity of field-wide “rules of thumb” such as the 3% rule, but opportunities to quantify effects more objectively can be expensive or impossible to implement when instrumenting new species. There is therefore a time-sensitive need for systematic reporting of biologging instrument characteristics based on known effects to animal welfare and data quality. We used 202 biologging impact studies from the last thirty years to draw broad, multispecies connections between instrument characteristics and animal physiology, behavior, and/or demography. We build on impact studies that focus on a single species, instrument type, or attachment method to offer solutions applicable across those taxa, technologies, and methodologies. From the literature, we distilled eight best practices for 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 propose a preliminary minimum reporting standard, informed by the literature and presented as a machine-readable checklist, that biologging researchers can include with their manuscripts or data submissions to provide data for future meta-analyses. We also present an example of a completed checklist to demonstrate the feasibility of such a standard and a plan for community input and adoption via the International Bio-Logging Society. Robust biologging infrastructure, beginning with a minimum reporting standard informed by the literature on instrument impacts, will facilitate the expansion of biologging across the globe and across disciplines while ensuring animal welfare and improving data quality. As biologging instruments become less expensive and more accessible, researchers, journals, and funders are better positioned than ever to broaden and implement these standards.

**Keywords** Animal welfare, Biologging, Impact, Reporting standard

\*Correspondence:

Allison R. Payne  
alrpayne@ucsc.edu

<sup>1</sup>Department of Ecology and Evolutionary Biology, University of California Santa Cruz, 130 McAllister Way, Santa Cruz, CA 95060, USA

<sup>2</sup>Department of Migration, Max Planck Institute of Animal Behavior, Radolfzell, Germany

<sup>3</sup>Department of Biology, University of Konstanz, Constance, Germany

<sup>4</sup>Center for Marine Biotechnology and Biomedicine, Scripps Institution of Oceanography, UC San Diego, La Jolla, CA 92037, USA



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## Introduction

Discoveries in ecology, physiology, and animal behavior increasingly come from instrumented animals that collect *in-situ* environmental and biological data [1–6]. Modern instruments can be small enough to attach to insects [7] or implant in goldfish [8], cheap enough for large sample sizes [9], and sophisticated enough to concurrently measure animal decisions and environmental conditions [10]. This “golden age” of biologging has allowed us to collect ecological data at an entirely new scale [6, 11], growing from individuals in a single location at a specific time of year to ecosystem-wide monitoring across seasons and continents [12]. As biologgers inform both basic and applied science across disciplines [13, 14], 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 [15–22]. Since then, technological advances have occurred more rapidly than researchers and regulatory bodies 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 [23]. However, several recent studies have emphasized the subjective nature of the rule [24–27]. Additionally, while the miniaturization of biologgers has resulted in smaller instruments, these smaller devices have been deployed on increasingly smaller animals [28], necessitating further conversations about minimizing instrument effects.

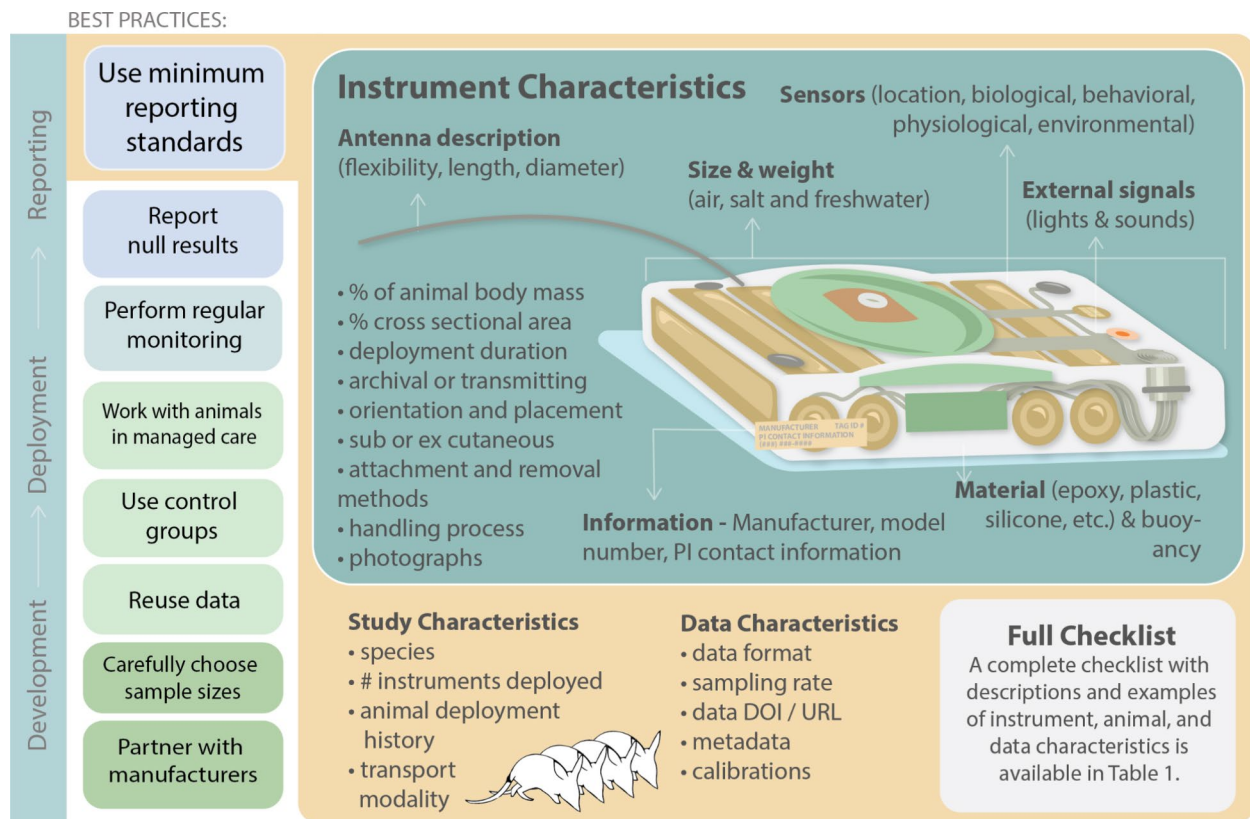
Novel, fundable, impactful science often demands larger sample sizes, increased sampling across demographic groups, smaller study species, longer study durations, and more data streams [29], all of which require more from the animals that carry biologging instruments. However, the acceleration of biologging science has far outpaced the development of reporting guidelines, which has hindered our ability to understand the effects of devices on the animals that carry them. As biologging efforts grow, ad-hoc reporting of instrument impacts will be insufficient to ensure animal welfare and scientific rigor [30, 31]. The biggest challenge in realizing these best practices is not technological ability or concern for the animals, but rather the lack of agreed-upon guidelines for documentation, 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 [32–35]. Biologging researchers have called for and proposed minimum reporting standards in the past, particularly for instruments that record animal location [15, 31, 36–39]. As biologging instruments become less expensive and more accessible, there is an increasing need for researchers, journals, and funders to broaden and implement these standards.

We used 202 biologging impact studies from the last thirty years to draw broad, multispecies connections between instrument characteristics and effects on animal physiology, behavior, and/or demography. We focused on biologging, rather than acoustic or radio telemetry, because of the larger diversity of biologging instruments and deployment methods; however, we attempted to incorporate relevant lessons from acoustic and radio telemetry when possible. We build on impact studies that focus on a single species, instrument type, or attachment method to offer solutions applicable across those taxa, technologies, and methodologies. We summarize the results of this literature review, with particular emphasis on the role of meta-analyses in identifying effects that were otherwise impossible to distinguish. We then propose best practices, based on the literature, for biologging researchers across all stages of a biologging study, from development to deployment to reporting. We identify minimum reporting standards as a prime opportunity for a low-risk, inexpensive, and impactful intervention, and we draw on the biologging literature to propose a minimum reporting standard that biologging researchers can use in their work. Finally, we offer an example of how the minimum reporting standard might be used in practice and outline a plan for community feedback and adoption.

## Review of instrument effects: considerations across disciplines and taxa

Previous impact studies are a very informative tool for designing and deploying biologging instruments. While many impact studies exist, they are almost always taxon or method-specific. Here, we synthesize 202 recent empirical biologging impact studies to generalize across transport modalities (walking, swimming, and flying) and research disciplines (physiology, behavior, and demography). Initial papers were queried from Google Scholar and Web of Science using keywords “biologg\*” and “impacts”. Relevant studies published between 1995 and 2025 were identified using backwards and forwards citation tracing. We focused on citation tracing because biologging terminology is unstandardized and has changed rapidly over the past two decades. This process, while not systematic, enabled us to efficiently capture broad patterns in biologging research across the last quarter century. The review and synthesis directly informed the development of broadly applicable best practices, detailed in Sect. “[Recommendations for biologging best practices](#)” and Fig. 1, as well as a detailed checklist to be used by future biologging researchers (See Sect. “[A minimum reporting standard for biologging instruments](#)” and Table 1). Details of all individual studies are available in the Supplemental material (Table S1).

Instruments may affect the animals that carry them across multiple disciplines, including physiology,



**Fig. 1** Recommendations for best practices during development, deployment, and reporting processes of biologging science, including detailed minimum reporting standards for instrument, study, and data characteristics. Sample instrument characteristics that would be useful to document and report with biologging manuscripts include size, mass, cross-sectional area, sensors, orientation, material, cross-sectional shape, and attachment/detachment method. For details and examples for all characteristics, see Table 1

behavior, and demography (Table 2). These effects are largely influenced by the interaction of instrument type and method of attachment with the animal's transport modality. In a hypothetical example, a geolocator (*instrument type*) attached to a flying bird (*transport modality*) with a leg-loop backpack harness (*attachment method*) may increase the metabolic costs of flight (*physiological effect*), which is associated with shorter foraging trips (*behavioral effect*) but does not affect chick growth rates (*lack of demographic effect*). Transport modalities, instrument and attachment types, and other relevant terms are defined in the Glossary (see supplemental material). It is important to note that while demography may not be measurably affected in this example, physiological or behavioral adjustments may nonetheless compromise the "natural" data collected by the instruments. Due to resource and logistical limitations, most studies can only feasibly report impacts for one discipline, 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 (Fig. 2).

### Effects on 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 if not fitted properly [40–42]. 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 [41]. Ear tags and expanding collars are a helpful tool for avoiding injuries when instrumenting juvenile walkers without disrupting their growth [43, 44].

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 [45]. For walking ectotherms, healing rates are affected by temperature-dependent metabolic rates, which can disrupt recovery

**Table 1** Details of recommended animal, instrument, and data characteristics to report in manuscripts, with examples

Characteristic	Description	Example	Units	Movebank term	Standard framework term
<i>Animal characteristics</i>					
Scientific name	Scientific name of the animal carrying instruments	<i>Mirounga angustirostris</i>	–	Animal taxon	ScientificName
Common name	Common name of the animal carrying instruments	Northern elephant seal	–	Animal taxon	CommonName
Number of animals instrumented	The number of animals that were instrumented with this configuration as part of the study	32 animals	Count	Can be derived from the data if the full dataset is archived	
Number of devices deployed on each animal	The number of instruments the animal is carrying during this deployment, including devices for which data are not analyzed in the current analysis. Characteristics should be reported in the “Device characteristics” rows for each instrument	2 (Satellite tag + VHF tag)	Count	Can be derived from the data if the full dataset is archived	
Average animal handling time	Average amount of time spent being handled. Notes on outliers should be included in the “Additional notes” section	125	Minutes	Capture handling time	TrappingMethodDetails
Average animal weight	Average weight of the animals measured at time of device deployment	170.6	Kilograms	Animal mass	OrganismWeightAtDeployment
Average animal length	Average length of the animals measured at time of device deployment	194.5	Centimeters	Animal length	OrganismLengthAtDeployment
Animal sex	Sex of the instrumented animals	Female, male	Male, female	Animal sex	OrganismSex
Animal age class	Age class of the instrumented animals. Juveniles refer to animals that are pre-reproductive age	Juveniles	Juvenile	Animal life stage (other terms allow definition of exact, minimum or maximum date of birth or hatching)	OrganismAgeReproductiveClass
<i>Device characteristics</i>					
Type of instrument	A general description of the type of instrument(s) being deployed	SCOUT DSA Satellite tag, Advanced Telemetry Systems VHF tag	–	Sensor type, Tag model	InstrumentType
Total instrument mass	Total weight of the instrument(s) in air	299	Grams	Tag mass	
Additional hardware mass	Weight of any additional hardware, such as a harness, collar, or housing	Negligible extra weight (splicing tape, mesh, zip ties, fishing line)	Grams	Tag mass total	
Percentage of animal bodyweight	Approximate ratio of instrument mass to animal mass	0.18	%	Can be calculated from tag and animal mass	
Device dimensions	Instrument length	85	Centimeters	Tag-dimensions (in progress)	
	Instrument width	85	Centimeters		
	Instrument height/depth	27	Centimeters		
Antennae / Light stalk	Description of instrument antenna/light stalk, if applicable	Stiff, flexible	Stiff, flexible		
	Antenna/light stalk length	18	Centimeters		
	Antenna/light stalk diameter	4	Millimeters		

**Table 1** (continued)

Characteristic	Description	Example	Units	Movebank term	Standard framework term
Cross-sectional shape	An estimate of the cross-sectional shape of the instrument. These may be rounded, square, cylindrical, etc. Include whether the instrument is streamlined or complex	Rectangular with rounded edges, streamlined	–	Tag comments	
Material	Material for instrument housing	Waterproof resin	–	Attachment comments	AttachmentMethod
Manufacturer	Instrument manufacturer	Wildlife Computers (Satellite), Advanced Telemetry Systems (VHF)	–	Tag manufacturer name	InstrumentManufacturer
Name / Model	Instrument name or model number	SCOUT-DSA-296 (Satellite), MM240B (VHF)	–	Tag model	InstrumentModel
Buoyancy	Buoyancy of the instrument(s) in seawater or freshwater (positive, neutral, negative) Buoyancy test type	Satellite and VHF	Unknown	Tag comments	
Signal production	Sounds, lights, magnetism, or other signals produced by the instrument	None	None	Tag comments	
Sensors	Sensors on the instrument that collect data. Adapted from [39]	3-axis acceleration, depth, temperature, wet/dry	Location, intrinsic, environmental	Embedded in the data (e.g., sensor type)	See sections Horizontal sensors, Vertical sensors, Environmental sensors, Physiological sensors, Accelerometry sensors
Orientation	Direction of instrument on the animal in relation to an external antenna	Satellite: antenna facing forward VHF: antenna facing backwards	Antennae forwards, antennae backwards	Attachment comments	
<i>Deployment characteristics</i>					
Location on body	Placement of the instrument on the animal's body	Head (Satellite), mid back (VHF)	–	Attachment body part	
Archival or Transmitting	Whether the instrument transmits data through methods such as ARGOS, or archives the data until the instrument is recovered	Transmitting, archival	Transmitting, archival	Tag readout method	
Photographs	Relevant photographs of instruments, placement, attachment, etc. included in an accessible format (i.e., jpeg)		–	Deployment image	
Instrument deployments	Number of instruments deployed	32	Count		
Instrument recovery	Number of deployed instruments that were recovered	28	Count	Relevant information can be stored in deployment end type, tag failure comments, animal mortality type	DeploymentOutcome
Attachment method	Method for attaching the instrument to the animal. Include whether the instrument is sub or ex cutaneous	Instruments were ziptied to a mesh patch, which was then glued (via quick-set epoxy) directly onto the fur	Direct attachment (via glue)	Attachment type, attachment comments	AttachmentMethod

**Table 1** (continued)

Characteristic	Description	Example	Units	Movebank term	Standard framework term
Detachment method	Method for detaching the tags	Removed manually upon recovery by cutting the zip ties. The glued patch is molted off during the animal's catastrophic molt	Manual	Deployment end type	DetachmentDetails
Handling process	Description of typical handling process, including drugs used and time spent in human care. Cite relevant permits	Healthy animals are chemically immobilized with an initial dose of telazol and sedation is maintained by follow up doses of ketamine and/or valium. Animals spend ~ 150 min in human care, which begins when they are immobilized and ends following an observation period post-handling. Tagging and sampling takes ~ 120 min. Elephant seal handling and sampling was approved by the University of California Santa Cruz Institutional Animal Care and Use Committee (#Costd-2009-1) and following guidelines set forth by the Society for Marine Mammalogy ethics committee. Fieldwork was carried out under National Marine Fisheries Service permits #23188	–	Capture method	TrappingMethodDetails
Average deployment duration	Average length of time that the animal will carry/carried the instrument	229	Days	Actual deployment duration can be derived from the data or using deploy-on date and deploy-off date	TrackStartTime, TrackEndTime
<i>Data characteristics</i>					
Instrument data format	File type of raw data output	.wch	–		

**Table 1** (continued)

Characteristic	Description	Example	Units	Movebank term	Standard framework term
Instrument data location	Location of raw and processed data, including DOIs. (e.g., Ocean Tracking Network, Movebank Data Repository, Dryad repository)	Not yet published	–	Citation	References, citation
Additional meta-data location	Where to find instrument calibrations and metadata that might be needed to analyze the raw or processed data, including details such as time zone	Not yet published	–	Tag calibration, geolocator calibration, tag settings	See sections Environmental data calibration, Physiological data calibration, Accelerometry data calibration

To improve archiving and opportunities for meta-analysis, many of these details can optionally be stored along with data, for example in the reference data (deployment-level information) on Movebank. For clarity, we include terms used to store this information in Movebank (“Movebank term”, MPIAB, 2024) or the standardized framework proposed by Sequeira et al. [38] (“Standard framework term”). Device characteristics could also be provided in documentation provided by instrument manufacturers to improve reporting likelihood and accuracy

**Table 2** Examples of effects to instrumented animals at different disciplines

Discipline	Examples of effects
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

from surgery or other instrument-derived injuries [46]. Physiological impacts to walkers are often attributed to disruption of fur or feathers, leading to compromised thermoregulation and therefore elevated energy expenditure [47] or reduced body condition [48].

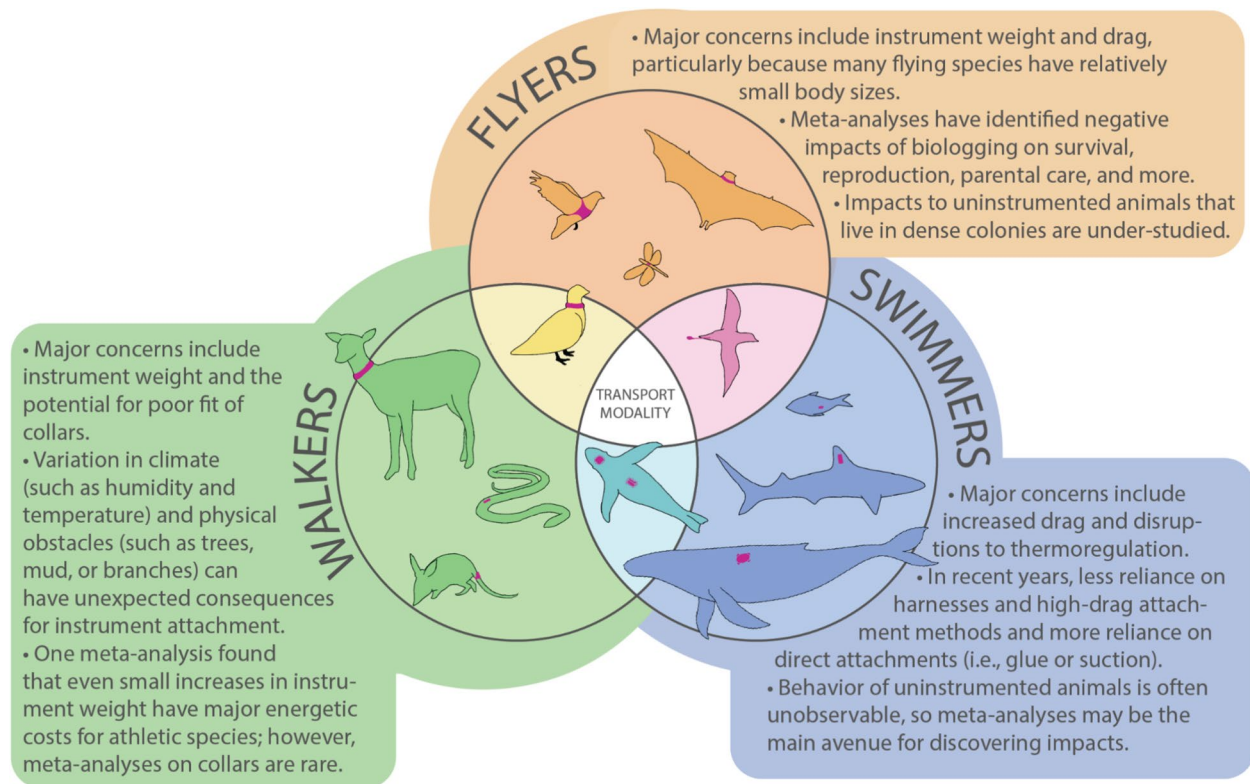
Effects on walking species are often assessed at the scale of behavior, and several studies have found significant behavioral changes among instrumented walking specialists. For example, a GPS collar weighing 1.8 kg reduced walking speed of zebras (*Equus burchelli*) while foraging by >50% relative to a collar weighing 1.2 kg [49]. 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 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 [50]. 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 [50].

For the fastest species such as cheetahs (*Acinonyx jubatus*), carrying these small instruments at top speeds was the equivalent of carrying a device weighing up to 54% of the animal’s body mass [50]. These findings informed our decision to include both instrument and animal characteristics in our minimum reporting checklist, including instrument dimensions and weight in air (Fig. 1, Table 1, Table S2). The behavioral effects 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 often must 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 relatively few meta-analyses available to address their impacts. A minimum reporting standard for animal, data, and instrument characteristics could help to fill this knowledge gap.

#### Effects on swimmers

In high-drag aquatic environments, minimizing mass and maximizing streamlining are both important to reduce instrumentation impacts [51]. Researchers instrumenting aquatic species employ a diversity of attachment methods, including (but not limited to) 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 [52]. Because the effects of these methods were published, the field has largely been able to move towards lower-impact methods [53–57]. While new harnessing techniques for seabirds are in development, the risk of drag and entanglement associated with harnesses may



**Fig. 2** Typical instrument attachment methods and a summary of their associated effects across walkers, swimmers, and flyers. Animals that use multiple transport modalities face concerns associated with each modality. We highlight the importance of meta-analyses for uncovering impacts to animal welfare or data quality across flyers, walkers, and swimmers

still lead to decreased survival compared to attachment methods such as glue and tape [58].

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 [59]. Biologging instruments can exacerbate thermoregulatory requirements by disrupting their insulation [60]. Instrumentation may impact species that rely on fur or feathers [48, 61] more than species that rely on blubber or other thermoregulatory adaptations [53, 57, 62, 63]. For example, cutting fur to remove glued instruments from northern fur seals (*Callorhinus ursinus*) significantly decreased the thermal resistance in the area around the cut fur; however, studies conducted on fur seal pelts showed that using a neoprene patch for attachment can mitigate negative thermoregulatory effects [60]. The potential for thermoregulatory impacts is one reason we included attachment method and location in the minimum reporting standard for instrument characteristics (Fig. 1, Table 1).

Injuries from instrument attachments on swimming animals are often minor. Glued and suction-attached devices may cause minor irritation [64], 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, the damage does not seem to affect growth or survival [65]. Similarly, injuries or subsequent infections are rarely reported for large whales instrumented with subdermal attachments via dart guns [54, 66]. Risk of attachment injuries may be buffered in swimmers because instruments are often placed flush to the skin to reduce drag, reducing opportunities for chafing, fouling, and entanglement; however, injuries may also be more difficult to observe in aquatic environments, leading to underreporting.

Biologging can allow for otherwise challenging underwater behavioral observations [67], 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 [68], cost of transport [69], and power consumption [70]. Some swimmers change their behavior to compensate for physiological impacts, such as reducing swim speed to compensate for increased locomotor costs [71]. 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 [72]. The

potential effects 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. 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) [51, 73–76]. While attachment methods are frequently reported in manuscripts, cross-sectional areas are not, likely because they can be difficult to calculate. We nonetheless recommend estimating cross-sectional areas whenever possible, particularly for swimming species.

Instruments are often implanted in swimming animals because implantation can mitigate risk of entanglement and decrease drag, particularly for long-term instrumentation [77]. Implantation is also frequently used for acoustic telemetry in fish, sometimes with highly standardized procedures across thousands of deployments [78–80] although society-level recommendations remain sparse [81, 82]. Implantation has also been used to successfully instrument pinnipeds, ursids, and mustelids, and specific best practices have been developed to guide sterilization, surgery, and release of pinnipeds [83]. In swimming birds such as penguins, implants can increase surface recovery periods. Implanted Adélie penguins (*Pygoscelis adeliae*) increased surface time due to reduced ventilation efficiency, likely because implants placed pressure on adjacent organs such as air sacs [84]. Overall, implants offer advantages for swimmers by reducing drag, which is very important in high-drag environments like water. However, implantation across walkers, swimmers, and flyers carries risks associated with surgery and recovery that should be carefully considered.

A swimmer's buoyancy may change as they dive, become pregnant, or gain/lose weight over the course of a migration [85]. Instrumentation can affect buoyancy, resulting in behavioral and physiological changes [26, 86]. For example, northern elephant seals (*Mirounga angustirostris*) carrying experimental buoyancy blocks adjusted their swimming stroke rate to maintain their swim speed [87]. Biologging devices—intended to record non-biased physiological or behavioral data—should be neutrally buoyant when possible, particularly for long deployments. We have included buoyancy as a part of the instrument characteristics reporting standard for biologging studies involving swimmers (Fig. 1, Table 1).

The potential for biologging instruments to increase predation risk via reduced mobility or signal production has been hypothesized, but is thus far unsubstantiated. However, there is evidence that telemetry instruments, such as acoustic transmitters, have a “dinner bell” effect for potential predators [88]. Many biologging 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 [89]. Sharks in particular forage by detecting the weak electromagnetic fields of their prey [90] and have been known to ingest instrumented prey [91]. Nonetheless, it remains an open question if carrying electronic instruments significantly increases the risk of mortality for swimming prey species. Additionally, instruments may also increase foraging success, as in the case of Antarctic fur seals (*Arctocephalus gazella*) instrumented with flash cameras that may have increased their ability to find prey [92]. Including signal production in the minimum instrument characteristics reporting standard could help answer open questions about the positive and negative effects of biologgers on behavior (Fig. 1, Table 1).

In summary, researchers instrumenting swimming animals must consider several unique constraints, including the increased drag, density, and heat capacity of water. Seabirds are more frequently evaluated for negative effects of biologgers than other species, possibly because there are opportunities to measure responses such as foraging or breeding success while the birds are on land. Nonetheless, a review of the seabird literature found that while 76.5% of papers discussed the effects of instrumentation, it accounted for a very small portion of the text, indicating a need for increased documentation [21]. 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.

### Effects on flyers

Instrumented flyers, including bats, birds, and insects, typically have smaller body sizes than walkers or swimmers and are often instrumented with backpack harnesses, rings, implants, or trailing attachments [4, 5, 93]. 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 effects of instrumentation on birds, the impacts to other flyers, especially invertebrates, are less well known [93, 94]. Major meta-analyses of avian species have been possible in large part due to the reporting of instrument characteristics such as weight in avian biologging manuscripts [21, 95], however, a recent review of 3,400 references found that 55% contained no information on potential effects, indicating that there is room to improve documentation procedures [96].

Powered flight carries the highest metabolic demands of any locomotor mode [97]. When instrumentation adds

to these already considerable costs, it can substantially affect daily energy expenditure and mass balance [24, 27, 98–102]. For example, homing pigeons instrumented for 25 days lost an amount of body mass equivalent to the mass of the instrument they carried [101]. 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 [24].

Although instrumentation best practices for avian flyers are well-established, instrumentation can nonetheless result in unexpected injuries. For example, electromagnetic radiation from instruments attached to the upper backs of ibises (*Geronticus eremita*) caused corneal opacity because of the birds' roosting posture [103]. In this case, careful monitoring during the study and a small shift in attachment location prevented damage in subsequent deployments. Instrument implantation carries additional risks because it requires a surgical procedure. However, once implanted, these instruments often cause fewer negative impacts for flyers than external devices [104]. External tags on flyers share swimmers' difficulties regarding drag [105], and collared flyers (typically bats) face the same issues with chafing and entanglement as collared walkers [106].

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 [107]. Researchers should 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 (Fig. 1, Table 1).

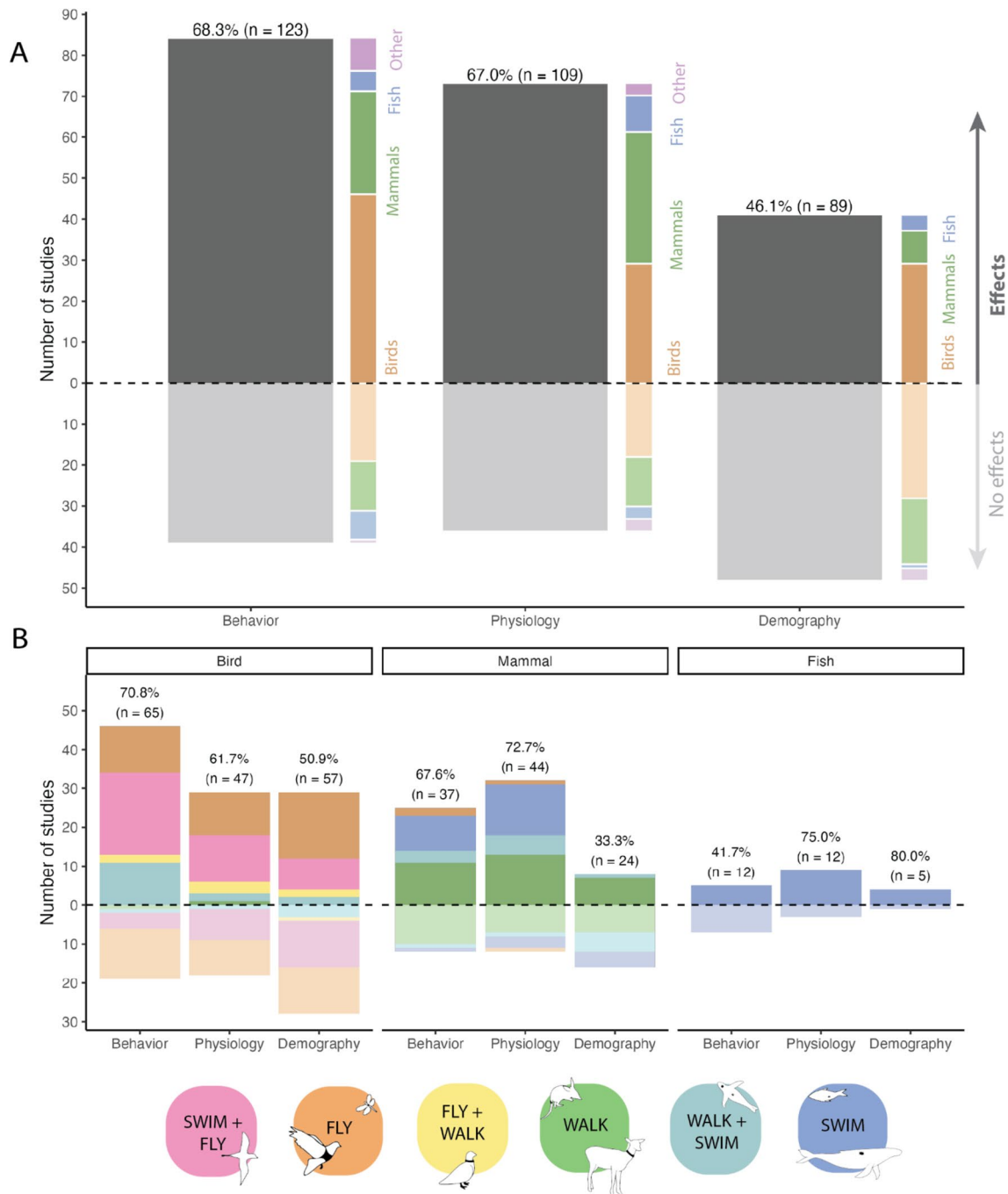
Some flying animals change their behavior to compensate for physiological or demographic impacts. Instruments can reduce the amount of time spent flying [108, 109], reduce flight speeds [110], and disrupt offspring provisioning behaviors [98, 111]. Additionally, many of the most commonly instrumented flying specialists undergo long migrations and carry their instruments across entire oceans or continents [7, 100, 112]. 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 [113]. Behavioral adjustments may allow species to compensate for instrumentation without altering reproductive behaviors such as chick provisioning [61, 114]. However, 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 reported negative effects of instrumentation on survival, reproduction, and parental care [25]. Intergenerational and partner-specific effects of device attachment have also been noted in multiple flying species [98, 111]. Seabirds, for example, are often monogamous, share parental investment, and live in large colonies where instrumentation can affect both the instrumented individual, un-instrumented co-parents, and offspring [108, 111, 115]. Un-instrumented partners, though not burdened with a physical weight, must compensate for their partner's behavioral changes to buffer effects on offspring [98, 111]. Elevated parental investment has been linked to the potential for reduced survival in many bird species, indicating potential downstream consequences for instrumentation [116, 117]. 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, as in some bat species. With many global populations of birds, bats, and insects at the highest levels of extinction risk [118, 119], it is imperative to understand and minimize the impacts of devices on demography.

### Summary: complexity of instrument effects

Across the studies synthesized here, biologging instruments are shown to have many potential effects across disciplines and time scales. It is difficult to compare these effects to each other in the same species, let alone across species from different transport modalities (Fig. 3). Additionally, instrumentation may be more disruptive in certain seasons, particularly during seasonal periods of mass change such as migration or molt [42, 101, 120]. Inter-annual 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 [121]. Furthermore, 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 [27]. Intraspecific variation can make impacts even less clear, particularly in studies without control groups or large sample sizes [48]. Device deployments on species that share many traits—including their use of multiple transport modalities—have produced contrary results [5, 53, 55, 72], illustrating the need for robust reporting even in well-studied systems.

Approximately 12% of the references we included studied more than one species, and 5% looked at five or more species. Eighty-four percent of multi-species studies reported impacts, compared to 62% of studies overall. We did not distinguish between studies that focused on instrument effects versus studies that opportunistically documented effects, thereby likely overestimating the



**Fig. 3** **A** Studies from our non-exhaustive review of biologging studies that quantify the presence (above the horizontal line,  $y=0$ ) or absence (below horizontal line) of impacts on behavior, physiology, and demography ( $n=202$ ). Bars above the dashed line indicate studies that found effects of instrumentation; bars below the dashed line indicate studies that did not find an effect. Studies are also broken down by broad taxonomic group. Percentages refer to the number of studies that found impacts out of  $n$  studies in that category and for that taxa. All impacts, even minor ones, are considered as a “Yes” due to the subjectivity of such characterizations. Some studies appear multiple times (i.e., the same study may find impacts in multiple disciplines, or may find impacts in some disciplines but not in others). We focused on papers published in the last thirty years due to major differences in best practices prior to the last few decades of biologging research. A detailed bibliographic database of all papers represented in this figure is available in Table S1, containing information about species, attachment type, and specific instrument impacts. **B** Number of studies on instrument impacts across three major groups: birds, mammals, and fish. Each category is color-coded by transport modality. Reptiles, insects, and mollusks are also included in panel A as category “Other”, but were excluded from visualization in panel B

prevalence of dedicated impact studies. Of all studies that reported impacts, few explicitly described sample size selection, control groups, pilot studies, impact monitoring strategies, instrument characteristics, or open data strategies. This information, which is not always included in the manuscript text or supplementary data in biologging studies, would allow researchers to continue building on the existing foundation of biologging knowledge. Efforts to bring this information into the published literature through minimum reporting standards could facilitate major breakthroughs in future scientific endeavors.

### **Recommendations for biologging best practices**

From our scoping multispecies review of instrument effects, we distilled eight best practices for biologging researchers, spanning the process of instrument development, deployment, and reporting (Fig. 1). We discuss the opportunities and challenges associated with each practice in an effort to be realistic about the everyday challenges faced by biologging scientists. We focus in particular on minimum reporting standards as a low-cost, high-impact way to promote animal welfare and data quality (detailed below and in Table 1).

#### **Establish partnerships during the design phase**

Partnerships between instrument manufacturers and researchers can facilitate the development of low-impact instruments [39]. Researchers can provide expertise on which characteristics are important in their study system (e.g., hydrodynamic shape, attachment, battery size, buoyancy, remote release, etc.). Instrument manufacturers can use their engineering and design expertise to make feasible adjustments and provide records of device characteristics that may be difficult for individual researchers to measure, such as buoyancy and cross-sectional area. Researchers and engineers can use computational modeling to test new sensors [122], calculate device effects [123], and optimize designs and positions [75]. Furthermore, large-scale biologging initiatives can collaborate with manufacturers to incorporate their knowledge into the initiative's guiding documents and best practices [13]. While these partnerships have few risks and many potential benefits, it can be a time-consuming process. These relationships will therefore be most fruitful if scientists can clearly describe the needs of both the individual and the community.

#### **Carefully choose sample sizes**

Selecting a sample size is a crucial part of biologging study planning [9, 124]. While some experimental biologging studies are limited in sample size due to the expense of instruments, researchers may be able to reduce their sample sizes depending on the scale of their question. At the same time, researchers should identify a minimum

sample size to ensure that the data they collect will be able to answer their question. Ensuring appropriate sample sizes conserves resources and reduces the number of individuals that may experience negative impacts from instruments [17, 125].

#### **Minimize deployments by using existing data where possible**

After defining the research question, required sample size, and other data requirements, researchers should assess whether existing data could meet some or all of their data needs. A search for relevant data includes reviewing published literature and searching biologging databases [126, 127] for relevant projects. Researchers can contact authors or data owners to discuss the proposed data use, confirm whether the data are suitable for the question, and request data sharing if needed. While data sharing agreements are common among major journals and funding sources, biologging data is not always discoverable or accessible [128, 129]. Overall, existing data will not be sufficient to answer all or even most questions, but data reuse can prevent animals from being unnecessarily re-instrumented and expand the impact and rigor of novel biologging data [130].

#### **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 [131]. However, there may be significant logistical, financial, and ethical constraints to implementing this practice. For example, for some species, such as pelagic sharks, most uninstrumented behavior may be unobservable. While not always possible, this practice can help detect instrument impacts and assure that biologging findings are generalizable to the larger population [132].

#### **Assess potential effects on animals in managed care**

Testing the effects 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 specific instrument characteristics and attachment methods [71, 133]. This practice requires careful collaboration with veterinarians and other animal care providers to minimize the risk of injury, and it is not an option for species that cannot be kept in captivity. Animals in managed care may exhibit behaviors specific to captivity, and their responses may not always reflect the responses of their

wild counterparts. Nonetheless, testing for short-term impacts may direct researchers towards small adjustments that can improve welfare during deployments on wild animals.

#### **Monitor studies regularly for signs of instrument effects**

Researchers should pay close attention to signs of physiological, behavioral, or demographic impacts and be ready to consider changing protocols during the study to minimize impacts. Small changes such as attachment method (e.g., amount of glue used) and location (e.g., a few centimeters forward or backward) can result in large improvements for animal welfare [45, 103]. However, drastically changing protocols can undermine a study's standardization practices and statistical power, highlighting the need to apply preventative best practices early in the scientific process. The potential for study results to change as protocols are updated emphasizes the importance of detailed protocol records and instrument metadata.

#### **Report null effect results**

Publications that report negative effects are more common than those that report null effects, at least in part because of the difficulty of publishing null results [30]. In our non-exhaustive review, nearly two-thirds of studies found a negative impact of instrumentation, which may partly be explained by the bias against publishing null results (Fig. 3). 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 [134]. Although they can be time consuming and are not currently incentivized, overall reports of null impacts are very valuable to the biologging community and should be treated as such. Complementary to the need to publish null results is a need for more research specifically aimed at assessing the effects of instruments on animals [135]. Furthermore, concerted community efforts to bring unpublished knowledge into the published literature (e.g., [18, 136]) greatly benefit the field of biologging by formalizing decades of experiences and sharing helpful anecdotes.

#### **Archive data according to minimum reporting standards**

Unlike fields such as genomics, biologging does not have a central data repository or standardization practice [31, 36, 37]. However, many publicly-searchable biologging databases exist that support public and restricted sharing [126, 137] in harmonized, documented formats [38, 138]. Collected data should be stored in one of these repositories, or a generalist repository (e.g., Dryad), and include

relevant reporting characteristics (Table 1). By making data publicly available whenever possible, and maintaining updated contact information on data platforms, data can be more easily reused [138]. Reporting the recommended characteristics together with the original data in a structured format can enable queries across hundreds or thousands of projects [139] and enable future evaluations of biologging impacts. While biologging researchers sharing their data should be sensitive to issues of conservation [140] and data sovereignty [141, 142], in general data-driven questions and global collaborations will help researchers to reuse and re-analyze data for new discoveries [12, 39, 143, 144], which in turn increases the impact of data collected by animals.

#### **Utilize minimum reporting standards in manuscripts**

It is unreasonable to expect every study to evaluate every potential instrument impact. However, a minimum reporting standard for biologging instruments represents a single solution that supports all researchers. To this end, all biologging studies should include descriptions of instruments and attachment methods [31]. 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. Although it will require substantial community effort, adopting a minimum reporting standard is a low-risk, high-reward next step for quantifying and minimizing instrument impacts. We detail our proposed minimum reporting standard and share an example in Sect. "[A minimum reporting standard for biologging instruments](#)".

#### **Summary: the need for standardized best practices across the scientific process**

These best practices are broadly applicable regardless of the unique challenges of each discipline, study system, or step in the scientific process. They are directed at researchers or practitioners who are designing and executing biologging studies. Instrument manufacturers also play a role in enabling these best practices by documenting information about their devices that may be difficult or impossible to know otherwise, such as the materials and the upper and lower limits of signals produced. Model-specific device information is often available from commercial tag producers, but with varying ease of access and level of detail. Large-scale biologging initiatives such as Animal Borne Ocean Sensors [13] offer opportunities to include instrument manufacturers in the creation of guiding documents, which in turn helps create governance structures and community cultures that prioritize greater transparency between manufacturers and researchers.

In the future, increased availability of instrument details from manufacturers could play a key role in

supporting transparent biologging research at scale. We encourage device sheets to be made available online by manufacturers in as much detail as can appropriately be shared with the public for both current and older models. The sensor descriptions could be provided using existing standards such as the Open Geospatial Consortium's Sensor Model Language (SensorML). Such reporting could improve accuracy and consistency of reporting and allow researchers to extract information about studies that may not be contained in published papers.

### **A minimum reporting standard for biologging instruments**

Using generalizations from the known effects across taxa, we collated a list of instrument characteristics for consideration throughout the process of instrument development, deployment, and data dissemination. We propose that minimum reported characteristics include the instrument type, placement, weight, size, material, cross-sectional shape, manufacturer and model, attachment and detachment method, deployment duration, sensor list, signal production, and the intensity and frequency of signals (Fig. 1; Table 1). Reporting characteristics such as the ratio between instrument/animal body mass or the ratio between instrument/animal cross-sectional area, can help to evaluate, update, and develop “rules of thumb” that can be useful when developing new instruments and instrumenting new species. As biologging researchers, we are aware of the burden of additional bureaucracy imposed by reporting standards. We have attempted to be thoughtfully exclusive in selecting the reporting checklist categories so as to decrease the burden on researchers who may adopt it. The categories aim to provide structure and facilitate transparency, balancing the complexity of biologging tools with the highest priorities for future research.

#### **Sample reporting standard**

To demonstrate the feasibility of a minimum reporting standard for instrument characteristics, we present a case study based on an ongoing biologging research project. This project, which does not assess instrument impacts, involves deploying SCOUT DSA Satellite Tags (Wildlife Computers) on juvenile northern elephant seals at Año Nuevo Reserve, California USA. Members of this project completed the minimum reporting standard checklist as a proof of concept. While not all categories were relevant to the study, the approximations nonetheless quantify the biologging instrument characteristics in far greater detail than is typically reported in study methods (Table 1).

When the data from this project are published, they will be uploaded into a repository such as Movebank. Movebank and other biologging data repositories often allow researchers to report the details of instrument

characteristics. We have included the Movebank term for each characteristic that has an equivalent in our checklist, as well as the Standard Framework term from [38] when applicable. While this metadata can be useful for answering a variety of questions, collecting it is one of the only ways to ensure that future researchers will be able to assess the effects of instrumentation on animal welfare and data quality at scale. We therefore recommend that managers of biologging repositories cross reference our checklist with the requested or required metadata for data submissions. Researchers who do not plan to upload their biologging data to Movebank or a similar repository may instead consider attaching the checklist to their publications as supplemental material in a machine readable format, such as a .csv or .json file. Finally, efforts by journal editors and funders to champion reporting standards could provide a helpful incentive to improve rigor and reproducibility. For example, the *Cell* family of journals implemented the STAR methods reporting standard in 2016 [145]. These protocols became mandatory to address reproducibility and meta-analysis issues in other fields that are similar to what we experience as biologging researchers [146].

Standards and best practices are most useful when they incorporate the knowledge and experience of a diverse community of researchers. While many of the authors of this study are members or leaders in the International Biologging Society's Data Standards Working Group, our suggested best practices are biased by our own experiences. Nonetheless, we believe that this effort is a valuable launching point for broad efforts across our field. To consider this work in the context of the larger biologging community, our suggested minimum reporting standard will be open for comment from the community on the International Biologging Society's website. We have created a web app for the checklist, available at <https://allisonpayne.shinyapps.io/biologgingmrs/> with all source code on GitHub. We have a tentative plan for the adoption of this standard with the Data Standards Working Group, which will occur during a hybrid workshop, open to the entire community, at the International Biologging Society Meeting in 2027. During this workshop, we will receive and incorporate additional feedback and provide an updated recommendation. In the meantime, we invite feedback from experts, particularly those who use methods not covered by our review such as fish telemetry (see supplemental material). While these processes can be iterative and slow, broad adoption of these standard frameworks and practices, informed by decades of research on biogger impacts, will support rigorous biologging research into the future.

## Conclusion

One of the greatest barriers to biologging impact meta-analyses and systematic reviews is that information about instrument effects 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 [147]. One development that could scale the impacts of our recommendations is the creation of a meta-database of biologger deployments, the instruments used, and the associated instrument characteristics [31, 38, 137]. Such a repository could link these metadata to related papers and full datasets archived in other repositories. Gathering this information in one place would enable future meta-analyses and identification of effects that may not be detectable in individual studies. Further, it would encourage communication and collaboration between researchers across taxa, transport modalities, disciplines, and fields outside of biologging, such as agricultural animal research. In the meantime, minimum reporting standards are a low-investment, high-reward method for building robust biologging infrastructure. Eventually, standardized metadata will allow us to quantitatively refine our best practices and learn from past successes and challenges. Embracing open data and reproducibility will accelerate the pace of discovery in biologging data [148], ultimately allowing researchers to save time and money, reduce the effects on animals, and continue to publish cutting-edge science. 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.

## Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s40317-025-00438-w>.

Additional file1 (PDF 69 KB)

Additional file2 (PDF 57 KB)

Additional file3 (PNG 1401 KB)

Additional file4 (DOCX 38381 KB)

Additional file5 (XLSX 266 KB)

Additional file6 (XLSX 80 KB)

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## Author contributions

ARP, CMH, SCD, JMK-B, and RSB conceived the ideas and designed methodology; ARP and CMH performed the review; ARP analysed the data; ARP and JMK-B created visualizations; ARP and CMH led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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## Data availability

All data required to reproduce figures are included in Supplemental Table S1; the data and code have also been uploaded to Dryad (doi: <https://doi.org/10.5061/dryad.bcc2fqzsp>).

## Declarations

### Competing interests

The authors declare that they have no competing interests.

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