Animal Biotelemetry

COMMENTARY

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Technology wish lists and the significance of temperature-sensing wildlife telemetry

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Abstract

Telemetry has revolutionized studies in wildlife biology, ecology, physiology, and conservation. With the increased demand for telemetry, new technology has made great strides to enable long studies in harsh and remote areas on a wide variety of study species. As the climate crisis continues to impact animals, temperature-sensing telemetry has become a helpful technique for understanding the effects of climate change and how to protect wildlife from them. However, temperature-sensing telemetry and telemetry in general still pose technological challenges and accessibility issues for the researchers who use it. Currently available telemetry technology is expensive, too large and heavy for many study species, and cannot measure all variables researchers want to study. These technological improvements have especially been neglected for temperature-sensing telemetry, which may be underutilized given the current climate crisis. To understand why innovation has stalled, and where it should be directed going forward, we gathered opinions from researchers who use telemetry and from manufacturers that create and supply telemetry equipment. Our goal was to broadly describe the current technological landscape, compare it to what we envision for the future, and make suggestions for how to reach that future.

Keywords: Company, Innovation, Interview, Manufacturer, Survey, Technology, Telemetry, Temperature, Wildlife tracking

Introduction

Wildlife studies were originally confined to live animal trapping, surveys, and transects that provided snapshot ecological and physiological data. Capture–mark–recapture studies were possible for certain types of animals, but recapturing individuals to study how they change over time remained challenging or impossible for most animals until the advent of telemetry in the mid-1950s. Since then, advances in telemetry have revolutionized studies in wildlife biology, ecology, physiology, and conservation. The number of publications using telemetry to study animals has skyrocketed in the past 20 years (Fig. 1) as technology continues to improve and as transmitters become accessible to more researchers. During the current "golden age" of animal biotelemetry, advances in technology are allowing scientists to learn much more about wild animals, using less invasive, and therefore, more fruitful and relevant methods [1, 2].

An especially promising advance is temperature-sensing telemetry. Temperature-sensing telemetry (which *senses* temperature) combined with datalogging technology (which *records* temperature data) in the transmitters themselves, in receivers, or in separate dataloggers, allows researchers to remotely collect environmental or body temperature data without spatial or temporal bias [3]. As the climate crisis continues to impact animal distributions, movement, health, and interactions, among other factors, temperature-sensing telemetry will be pivotal. Altered temperature regimes are and will continue to be the driver of physiological stress and constraints [4]. Measuring temperature using telemetry

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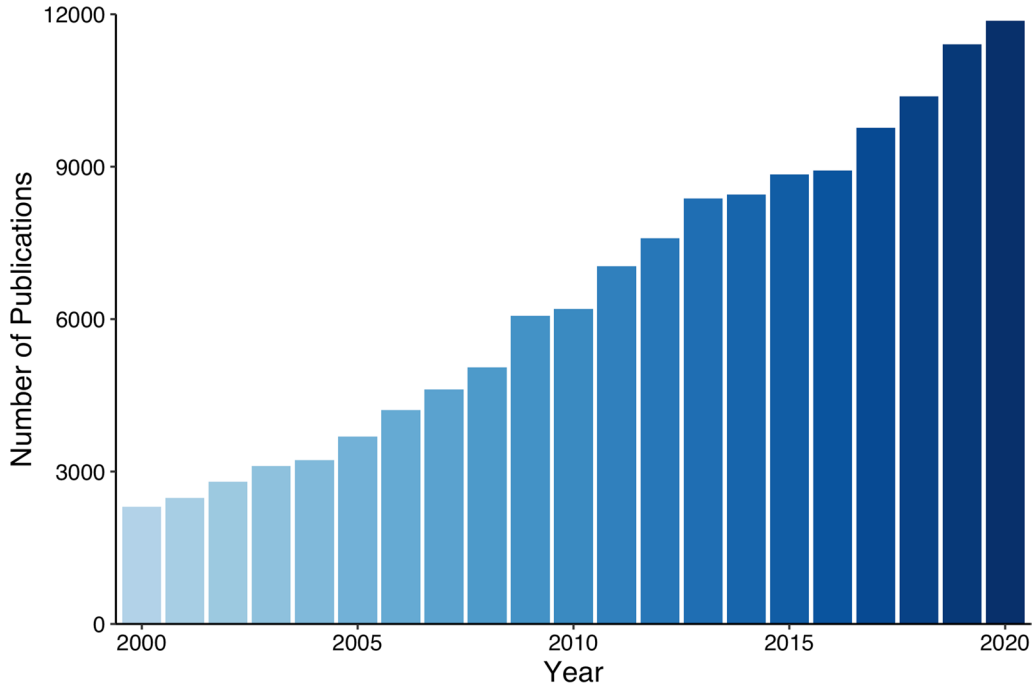


Fig. 1 The number of publications using animal biotelemetry has risen dramatically in the past 20 years. Data are from a Web of Science search conducted on 3 June 2021 for the following terms: wildlife telemetry, wildlife biotelemetry, wildlife tracking, animal telemetry, animal biotelemetry, and animal tracking

will help describe changes in environmental temperature and changes in behavior as a response. Ectotherms have emerged as model organisms to study these effects because environmental temperature plays such a direct role in their physiology [4, 5]. These data are essential for conservation efforts because continuous body and environmental temperature data can be used to predict the effects of climate change on at-risk populations [6]. Temperature-sensing telemetry can also be used to remotely collect data on both ectothermic and endothermic animals' activity patterns, from terrestrial surface activity [7] to marine diving behavior [8]. Clearly, temperature represents a key variable for physiology, ecology, and behavior, thus one might expect temperature-sensing telemetry to be a high priority for researchers and manufacturers. However, in our experience, temperature-sensing telemetry is underutilized, and its technological advances appear to have stalled. While temperature-sensing transmitters have enjoyed the same miniaturization as regular transmitters, temperature datalogging technology in receivers remains largely unchanged since the 1980s.

Additional areas of improvement include technology capabilities, size/weight, and price. In some cases, telemetry may not be an improvement on capture–mark–recapture studies because telemetry devices cannot measure the variables of interest. Although devices have undergone incredible miniaturization and cost reduction, further improvements could still be made so the technology is feasible for a greater suite of animals and more researchers. Even basic very high-frequency (VHF) radio telemetry remains out of reach for many researchers with smaller budgets, including many researchers from low-income countries. This amplifies scientific biases by excluding certain researchers from being able to access telemetry equipment, increasing the likelihood of parachute scientists conducting telemetry and thus perpetuating problematic colonial science [9–11]. Furthermore, scientists studying very small animals still face major challenges with telemetry due to the tradeoff between battery life and transmitter size/weight. Challenges with access to telemetry equipment and with the technology itself therefore remain, and this commentary serves to summarize opinions on these challenges from both the creators and users of the technology.

Researchers who use telemetry to study the ecology and physiology of a wide variety of animals, including endangered species and the effects of climate change, are greatly impacted by the technology available to them. Many factors impact the design and price of telemetry transmitters, sensors, receivers, antennas, software, and other equipment. Like all producers and consumers, the challenges and constraints faced by companies producing

telemetry gear and by scientists using it for research are often different. For example, transmitters may be paired with various sensors [12] that measure and log changes in the animal's behavior (e.g., by measuring speed or acceleration), physiology (e.g., muscular activity, sound production, temperature), or environmental conditions (e.g., dissolved oxygen, altitude). Many of these sensors represent niche equipment that are strongly desired by some researchers but may not be worthwhile for manufacturers to produce en masse. Companies producing telemetry equipment are typically private, for-profit businesses that must balance the price points of their equipment with researcher demand and the ever-changing landscape of research funding. Finally, manufacturers must respond to, and indeed anticipate, the technological needs of researchers, and in turn researchers are often constrained by manufacturer investment choices, creating an intricate dance between tech-users and tech-creators, the progress of which may have dire impacts for research on sensitive or endangered species in this current climate crisis and associated mass extinction.

We present this commentary to advocate for what telemetry advances could and should be made in the future. We aim not to describe what is currently possible, but what researchers *want* to be possible. We gathered opinions from researchers who use telemetry and from manufacturers that create and supply telemetry equipment to broadly describe the current technological landscape and to compare it to what we envision for the future. Telemetry technology includes Global Positioning Systems (GPS), VHF radio, and Argos satellite tracking. A given telemetry system may consist of various sensors that measure, transmitters that send, and receivers or loggers that record the data of interest [13]. However, in this paper, we refer to telemetry broadly because the opinions discussed apply to all telemetry systems. We surveyed 84 scientific researchers who use telemetry and interviewed representatives of 9 companies that design, manufacture, and sell telemetry equipment. We collected perceptions of telemetry equipment generally, but we also focused specifically on temperature-sensing telemetry to evaluate whether our perceived lack of user interest and manufacturer investment is evident, and to pursue reasons for this. We describe current implementations of temperature-sensing telemetry, assert the need for improved telemetry technology in general and increased focus on temperature-sensing telemetry, and make suggestions for how to achieve these key innovations. The information presented here will be a resource in the coming years for researchers planning to acquire telemetry equipment and organizing new studies, as well as for manufacturers deciding which technological directions may optimize their investment.

Researcher surveys

Methods

Throughout November 2020, we distributed an online Microsoft Form with a combination of free response, rank-choice, and Likert scale questions (Additional file 1). In our survey questions, we used the terminology "temperature-sensitive telemetry", which we define the same way as "temperature-sensing telemetry". We distributed the survey using social media (Twitter, Facebook) and via email to corresponding authors of papers published in the journal Animal Biotelemetry in the past 2 years and of papers publicized on telemetry company websites. Of the 84 telemetry users who responded to the survey, 23% were university faculty ($n=19$), 20% were postdoctoral researchers ($n=17$), 20% were graduate students pursuing either an MS or PhD ($n=17$), 16% were non-academic researchers such as those associated with government or nonprofit organizations ($n=13$), and 20% responded as "other" ($n=17$), with one non-response. We recognize that our survey has distribution and participation biases.

Survey responses were exported to Microsoft Excel for count data. Respondents could choose more than one answer choice for each question, so the percentages of respondents choosing a given answer sums to greater than 100% for most questions. SJW coded written free responses for keywords. We used X^2 tests to determine whether there was a significant difference in the frequency of temperature-sensing telemetry use based on study organism (endotherm versus ectotherm and by clade), study habitat, or device attachment method. The sample sizes vary for each test because respondents may have selected more than one option for a given question. For the analysis of study organism, each survey respondent was coded to study either endotherms, ectotherms, or both ($n_{total}=84$). For analyses of clade, habitat, and device attachment method, we excluded those researchers who selected more than one clade, study habitat, or attachment method because their incorporation of temperature may have only been related to one of the responses listed ($n_{total}<84$ for each of these tests). Figure 2 shows the full dataset with no exclusions made, so it does not perfectly reflect the X^2 test statistics and percentages presented in the results. We used R v4.0.3 [14] and tidyverse workflow [15] to create figures and analyze data. The survey and the use of data were approved by the California Polytechnic State University Institutional Review Board (Project 2020-183).

Current telemetry applications

Most of the respondents (56%) reported studying endotherms, 39% studied ectotherms, and 5% studied both. The number of study species listed by survey respondents

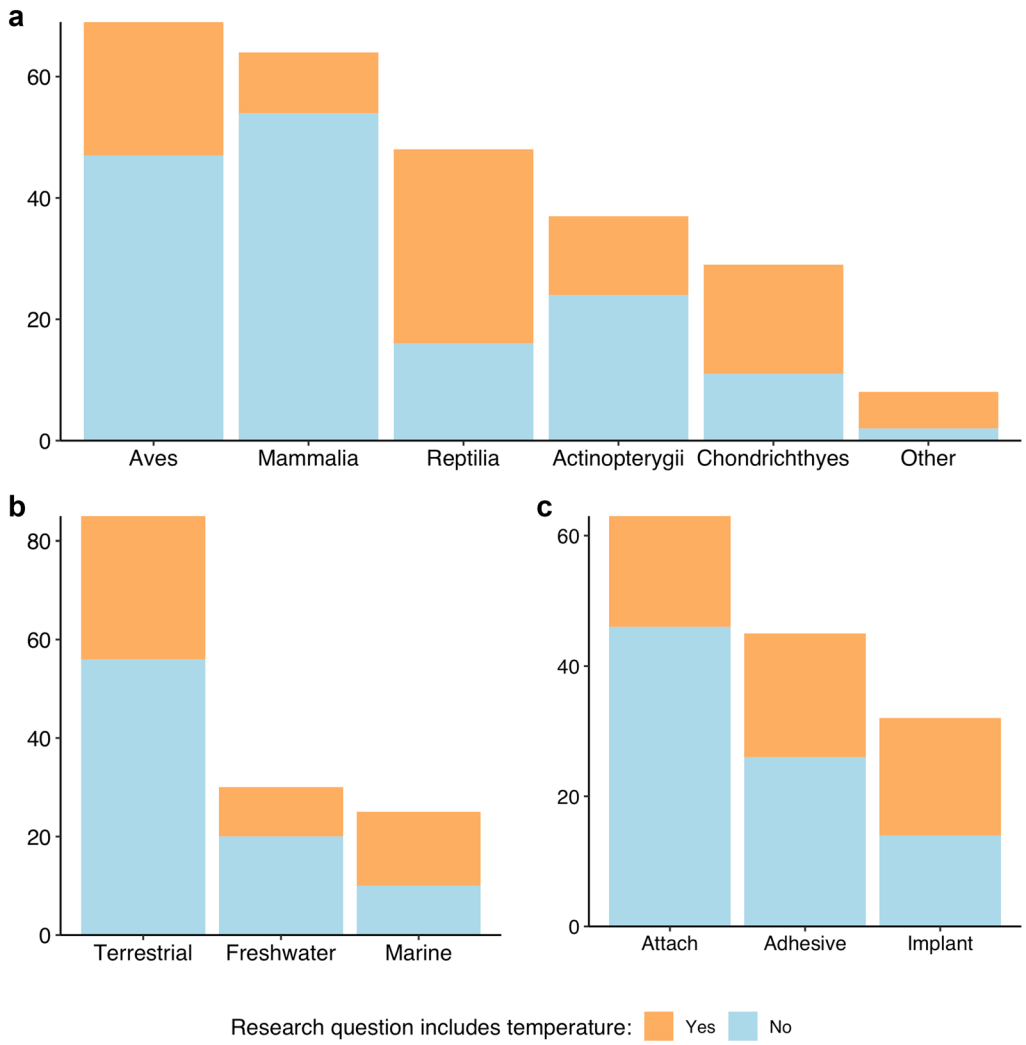


Fig. 2 Study organisms, habitats, and transmitter-animal pairing methods. Survey respondents ($N = 84$) indicated **a** their study organism(s), **b** their study organisms' primary habitat(s), and **c** the mode(s) of device attachment to their study animals. All vertical axes represent count data

totaled 255, although many were not listed to species-level. In order of popularity, birds (Aves), mammals (Mammalia), reptiles (Reptilia), ray-finned fishes (Actinopterygii), and sharks and rays (Chondrichthyes) were the most common clades of study animals in our sample of researchers using telemetry (Fig. 2a); other telemetry study species included amphibians, insects, and crayfish. Terrestrial organisms are the most tracked animals based on this survey (77% of respondents study them), followed by freshwater (25%) and marine (17%, Fig. 2b). Most respondents (65%) reported that they use external attachment methods such as a collar, waistband, backpack, or similar; 42% reported that they use adhesives such as glue or tape; 31% reported that they implant devices (Fig. 2c). Researchers reported using telemetry for a wide array of study questions, including animal movement, habitat use, behaviors, home range, survivorship, activity timing, sociality, management needs/outcomes, and more (Additional file 2).

Telemetry wish lists

Survey respondents were asked to rank their top priorities when selecting telemetry equipment, and the characteristics with the most first-choice rankings were weight, price, size, variables recorded, and battery life (Fig. 3). Durability, data storage, and receiver range were also priorities but were comparably less important.

Researchers are only somewhat satisfied with the currently available telemetry equipment they use. Most survey respondents are unable to measure everything

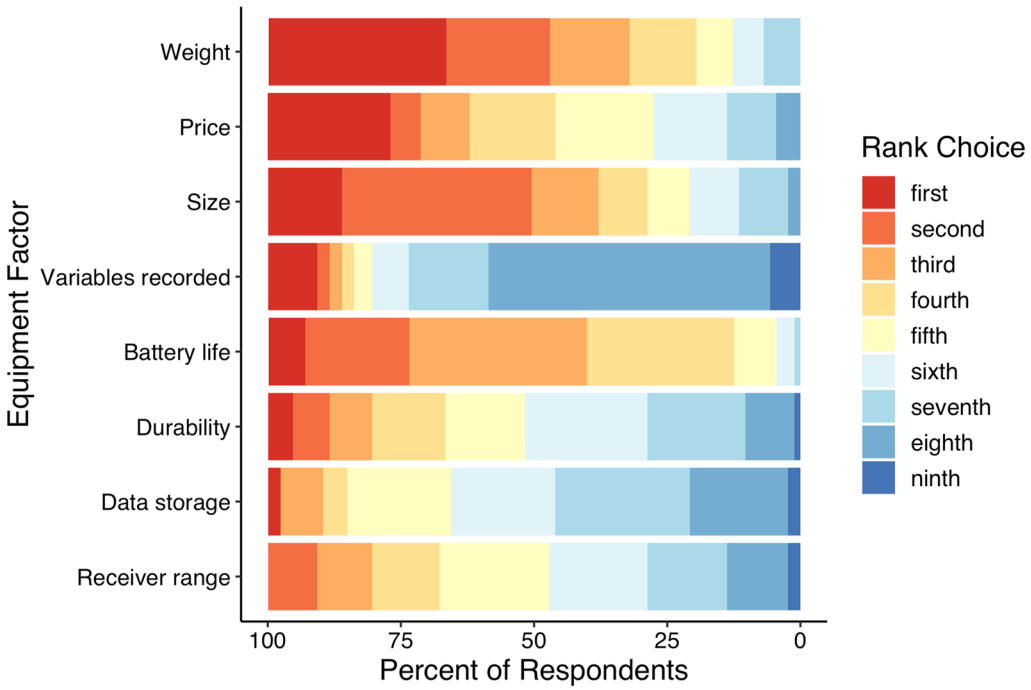


Fig. 3 Researchers' most important telemetry product characteristics. Survey respondents ($N = 84$) ranked what factors are most important to them when selecting telemetry equipment

desired with the equipment they use (Q11, Fig. 4). We asked respondents what variables they want to be able to measure that cannot be measured/recorded by currently available telemetry equipment (Additional file 1, Question 7). We used these responses to create a "wish list" of variables that respondents wished their current telemetry devices could measure and transmit/record. Some of the additional variables with the highest demand among survey respondents included assessing movement and behaviors via accelerometry (12%), and measuring/recording environmental temperature (6%), heart rate (6%), internal body temperature (5%), and audio and/or video recordings (5%). See Additional file 2 for a full list of variables respondents wished their equipment recorded.

Respondents reported that their most time-consuming technical difficulties when using telemetry equipment for studies included equipment running out of battery power prematurely (19%), equipment failing or breaking (18%), issues with data or equipment retrieval (17%), and difficult data formatting (13%; Additional file 2). Conversely, we asked respondents to imagine there were no technological limits and describe traits of their ideal, "fantasy" equipment that would meet all of their research needs and interests if anything was possible (Additional file 1, Question 13). Whereas the variable wish lists described above referred to what variables researchers wanted telemetry to measure and record, fantasy equipment refers to any and all telemetry product characteristics. The top ten fantasy equipment characteristics were smaller and lighter transmitters (60%), longer battery life (54%), more variables measured (52%), lower cost (23%), more data storage (22%), better durability for rough environments, including waterproofing and for use with reckless animals (21%), longer signal range (18%), remote data download ability (17%), higher measurement frequency (13%), and more precise measurements (13%; Additional file 2). Survey respondents suggested solar power to extend battery life and urged that including a battery indicator would be immensely helpful. In an ideal world with no technological constraints, researchers hope for all these capabilities and more in ever-smaller devices.

Temperature-sensing telemetry

33% of respondents reported that they incorporate either environmental or organismal temperature into their telemetry (Q12, Fig. 4). Respondents who reported studying ectotherms incorporate temperature into their telemetry studies significantly more often (57%) than respondents studying endotherms (15%; $n = 84$, $X^2 = 17.0$, $df = 2$, $p < 0.001$; Fig. 2a). The frequency of temperature-sensing telemetry use was also significantly different across study organism clades ($n = 70$, $X^2 = 19.3$, $df = 5$, $p = 0.002$; Fig. 2a): 16% of respondents studying

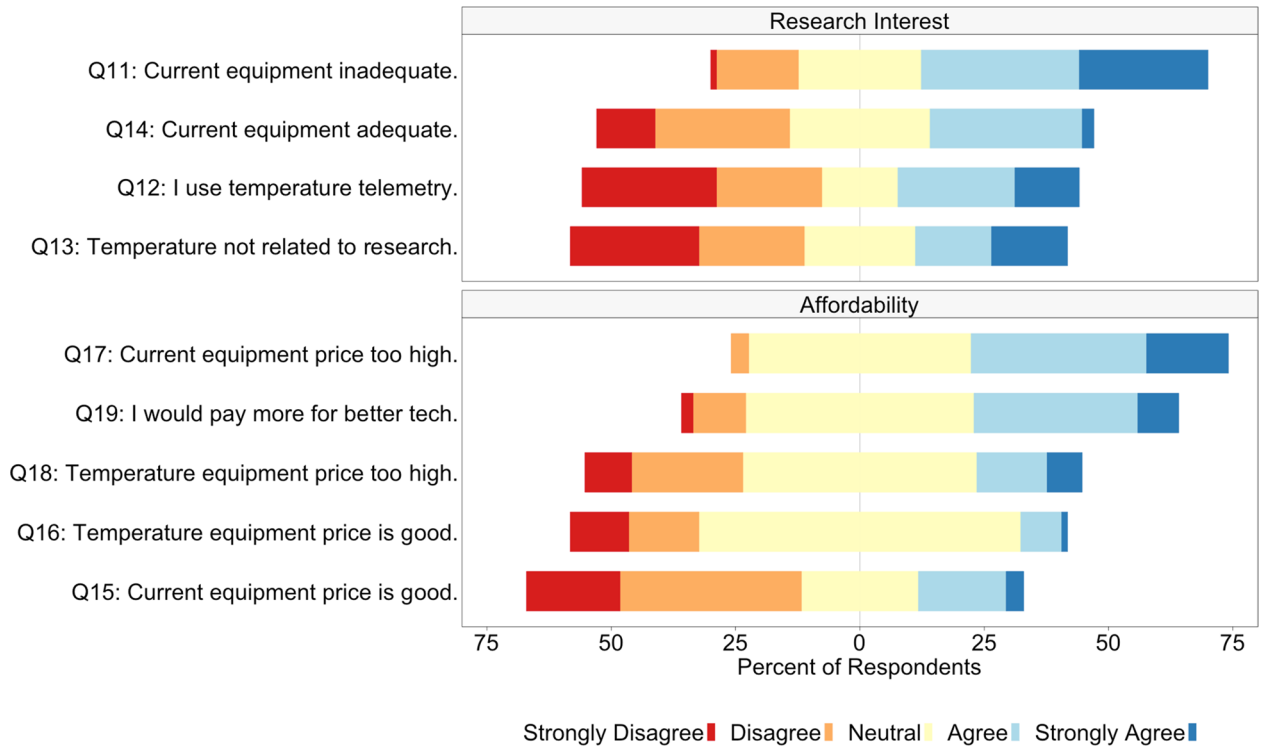


Fig. 4 Researchers' opinions on the research application and affordability of current telemetry equipment. Survey respondents ($N=84$) indicated their satisfaction with the variables measured by current telemetry equipment, whether or not they use temperature-sensing telemetry, and their opinions on the pricing of telemetry equipment. Questions abbreviated for the figure (e.g., temperature equipment refers to temperature-sensing telemetry equipment); see Additional file 1 for full questions

birds incorporate temperature, with 13% for mammals, 56% for reptiles, 20% for ray-finned fishes, 100% for sharks and rays, and 75% for "other" organisms, which consisted of ectothermic amphibians and invertebrates. Researchers studying marine organisms were most likely to incorporate temperature (71%), followed by terrestrial (30%), then freshwater (20%). The frequency of temperature-sensing telemetry use was not significantly different among study animal habitats ($n=67$, $X^2=5.6$, $df=2$, $p=0.059$; Fig. 2b) or major mode of device attachment ($n=53$, $X^2=4.7$, $df=2$, $p=0.096$; Fig. 2c).

For respondents who do not use temperature-sensing telemetry, 37% said that temperature was unrelated to their research questions, 8% said it was unnecessary because there was not sufficient temperature variation to measure in their context, and 5% had never considered the possibility of including temperature in their telemetry studies. Some researchers may have wanted to include temperature but were unable to do so due to cost (13%), logistics of product trade-offs and availability (12%), size/weight limitations (10%), and battery lifespan (2%; Fig. 5). Respondents overall said that the current price of telemetry equipment is too high (Q15 and Q17, Fig. 4), but temperature-sensing telemetry users do not share this opinion as strongly (Q16 and Q18, Fig. 4), and may even be willing to pay more for better temperature-sensing telemetry technology (Q19, Fig. 4).

Company interviews

Methods

To understand telemetry product development and predict future advances, we interviewed representatives from companies that manufacture telemetry equipment over the phone or via email correspondence. We compiled a list of companies to interview that we already knew of or that we found in a basic Google search prior to distributing the researcher survey. Of the 17 companies we contacted, 11 responded to our queries, and 9 followed through with the interview (Additional file 2): Advanced Telemetry Systems, Inc. (ATS; Isanti, Minnesota, United States), Cellular Tracking Technologies LLC (CTT; Rio Grande, New Jersey, United States), Holohil Systems, Ltd. (Carp, Ontario, Canada), Innovasea Systems Inc. (Canada; Chile; Norway; United States), mOOvement (Brisbane, Queensland, Australia), Microwave Telemetry, Inc. (MTI; Columbia, Maryland, United States), TechnoSmart Europe SRL (Guidonia, Rome, Italy), Vectronic Aerospace Inc. (Coralville, Iowa, United

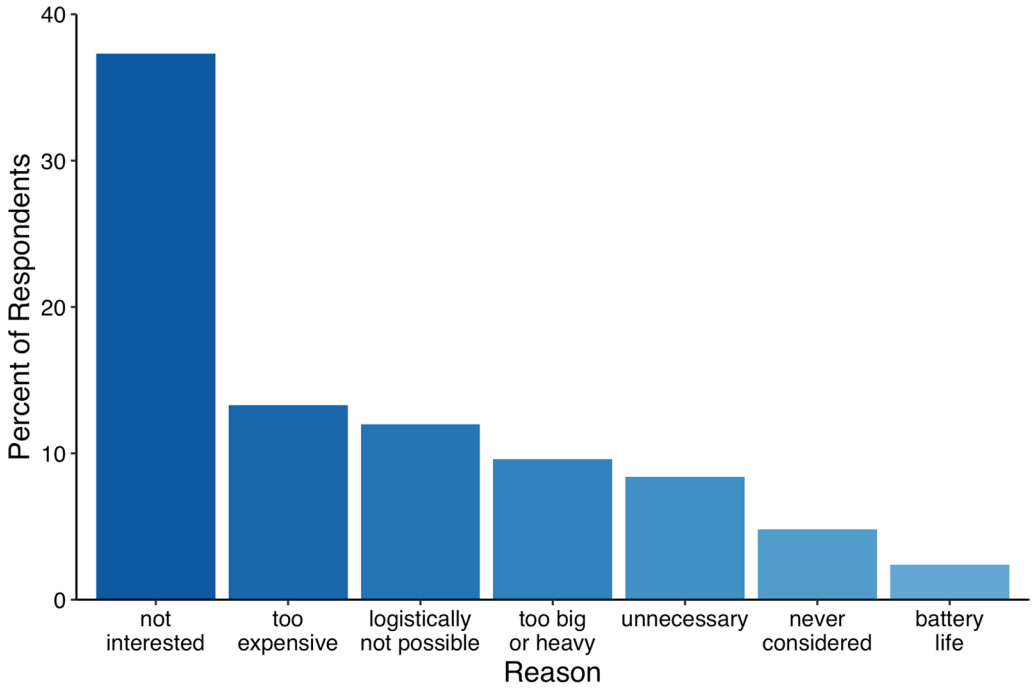


Fig. 5 Why researchers do not include temperature. Survey respondents who do not use temperature-sensing telemetry equipment ($N = 56$) indicated why they do not use it

States), and Wildlife Computers, Inc. (Redmond, Washington, United States).

Our aim was not to draw conclusions about the popularity of companies or to compare their products, but rather to understand product development and to gauge whether manufacturers' perception of researchers' desires align with the needs reported by survey respondents. We asked manufacturer representatives questions about their product development and market perception generally, as well as questions directly related to temperature-sensing equipment (Additional file 3). The interviews and the use of data from them were approved by the California Polytechnic State University Institutional Review Board (Project 2020-183), and we received permission from the interviewees that we could include their company's name and responses in our paper.

Current product development

Eight of the nine companies we interviewed said that they use customer feedback and requests to determine what directions to take for product development and improvement. Other ways product development may be directed included demand, predicting research trends, and company goals and interests, each of which were listed by 2–3 companies. Several of the companies we interviewed reported that they rely on conferences to engage with researchers, but more companies reported that they rely on unsolicited feedback and casual conversations with customers to gauge interest in new and improved products. Approximately half of the companies we interviewed said that miniaturization and improving reliability are the most important product characteristics to improve, with extending battery life/efficiency, improving durability, and lowering price also listed by several companies. Although they stated that they are actively working on improving each of these, miniaturization was of primary importance. However, companies feel inconsistent pressure to make these improvements. Some companies reported constant demand for new and improved products, while others reported very little.

According to manufacturers, the equipment characteristics that researchers desire tend to create tradeoffs, where each innovation comes with a drawback. For example, measuring an additional variable uses more battery, makes the device larger and heavier, and/or increases its cost. Additionally, a common sentiment from companies was that new and improved products are an endless cycle: before manufacturers can even develop and refine one technology, researchers have already come up with new research questions that necessitate the development of another new technology.

Temperature-sensing telemetry

Company representatives reported that between 0 and 15% of their customers are interested in incorporating temperature into their equipment, with most estimating between 5 and 10%. Since the baseline demand for temperature-sensing telemetry equipment is so low, almost all the manufacturers we interviewed reported that their perceived demand for new and improved temperature-sensing telemetry equipment was essentially nonexistent. Some companies automatically include temperature sensors in all products, and others can incorporate temperature sensors into any product. These sensors most often record ambient temperature or animal surface body temperature. Some companies also produce surgically implantable temperature-sensing transmitters that can yield data on animal core body temperature. For those companies that produce temperature-sensing transmitters and feel demand for improvement of temperature-sensing products specifically, they are currently working to make temperature measurements more precise and the transmitters smaller and less expensive, although this applies to few companies.

Technological trade-offs

After nearly a century of telemetry innovation, there is now a wide array of telemetry devices with an even wider array of potential applications [1, 2, 12, 16]. Telemetry now enables studies on topics such as animal movement and migration [17–19], physiological processes [20, 21], or social interactions [22], and our survey respondents compiled an even longer list of current applications (Additional file 2). However, the survey responses also show how many research interests still cannot yet be satisfactorily investigated using telemetry.

Our survey of researchers who use telemetry to study animals and interviews with the manufacturers that produce telemetry equipment revealed only partial alignment between supply and demand. For example, both researchers and manufacturers identified transmitter miniaturization as a top priority. However, one overlooked issue brought up in the survey responses, and in a recent review paper focusing on satellite telemetry [23], was difficult data formatting. This was the only issue that did not seem to be on any company's radar in our interviews. An inability to understand data structure and analyze it could be a barrier to researchers wishing to begin using telemetry or simply looking to switch telemetry manufacturers. A universal telemetry data structure, perhaps agreed upon by a coalition of company representatives and data scientists, could go a long way to inspire new telemetry users and applications.

Overall, companies recognize most of the wish list variables and fantasy equipment traits compiled in the survey responses, but they maintain reservations about creating new technology. Researchers can be eager to get new technology on an urgent timeline, but seemingly simple innovations can take years to develop into something actually effective. Researchers' demand for improved telemetry equipment has already pushed huge technological advances [1, 2, 24, 25], and based on researcher demands and company plans, these improvements will continue. Equipment manufacturers are indeed working hard to meet researchers' most pressing needs, but the technology will always lag behind the new applications desired.

Certain innovations are unlikely because there is not enough demand, they would be too difficult to engineer, or the product would not be profitable enough. For example, researchers always want to get the same or better technology in an ever-smaller package, but there need to be better batteries available before that will be possible. Survey respondents had numerous wish list variables that they want telemetry equipment to be able to measure; however, most variables were only listed by < 5% of respondents (Additional file 2). The amount of product development necessary to create a niche product for a single project is unlikely to be financially feasible for the manufacturer or the user. Many innovations are simply not feasible because the number of buyers would be so small.

Even when certain product characteristics can be achieved, there is usually an associated downside such as shorter battery life, larger/heavier transmitters, loss of a different sensor, and especially increased product cost. Survey respondents wrote about having to make decisions based on these trade-offs with sample size, transmitter size/weight, and battery life. When it comes to telemetry equipment, there is not a single product that will fit the needs of every study. This may be one reason why researchers reported using such a diverse array of manufacturers ($n = 42$, Additional file 2), some of whom specialize in specific technologies. Unfortunately, it seems researchers are often unable to find the right company for a product that will most closely match their needs, as most of the respondents' desired wish list variables have been recorded using biotelemetry [2]. To navigate the vast array of telemetry manufacturers, products, and applications, several reviews and guides are informative [12, 16, 23, 26].

Financial obstacles

Telemetry, along with much scientific research, is generally dominated by well-funded projects and universities in wealthy nations. The cost of telemetry devices limits the number of variables that can be measured, animals that can be tracked, and researchers who can use it. Even

if product costs were to fall, accessibility is likely to continue to be stratified. Many companies offer equipment refurbishment, which can decrease costs in subsequent years of telemetry, after getting started. Thus, one way to make telemetry studies more equitable could be for companies to sell refurbished equipment at discounted prices, as some already do.

Despite already-high costs for telemetry equipment, some survey respondents still indicated they are willing to pay top dollar for a device that measures *everything* they want it to. However, interview responses from companies suggest they disagree. Researchers state that they are willing to pay more money for their ideal equipment, but companies argue that in the end, idealized equipment is too expensive to be feasible. Companies are actively working to improve many product characteristics, but there will likely be a standstill on many niche product characteristics, at least from the large telemetry companies, until there is enough demand to satisfy manufacturers' need for profit. This presents telemetry innovation with a predicament: certain product characteristics are unlikely to be developed unless they are mainstream enough to garner widespread use and thus sales and profitability, but how can those product characteristics become mainstream before they are developed and available for purchase?

Potential product development

One solution is to put the responsibility of product development on the researchers. Several survey respondents reported that they use "DIY" equipment to measure their desired variables on a reasonable budget. While some researchers actually engineer their own transmitters or other equipment, others modify existing technology. One example of this is user-modifications to reduce the size and weight of Thermochron iButton temperature loggers, which are often used with telemetry for thermal ecology studies [27–29]. In addition, for two of the most prevalent telemetry equipment problems—data download and battery life—survey respondents proposed potential fixes using drones and rechargeability. For example, using drones as mobile telemetry receivers could remove limitations due to poor signal range, animals in inaccessible environments, and other challenges [30, 31]. Alternatively, if receivers were smaller and many could be purchased for a given project, they could be placed throughout the study species' range to help track movement and habitat use where GPS cannot be implemented for size or signal limitations. For transmitters attached to organisms externally, solar power is already a known avenue for battery rechargeability [32]. Could internally implanted transmitters be recharged wirelessly by placing the animal with the implanted device inside a charging box? This could extend study lifetimes indefinitely without necessitating additional surgical procedures. Other promising technologies include powering transmitters via kinetic energy of the moving animal (e.g., [33, 34]). Some companies prefer to remain within their product expertise, but many companies will work closely with researchers to develop relatively simple, small, pragmatic product characteristics for certain projects.

Alternatively, in the absence of a single product that fulfills all their niche demands, several survey respondents reported using more than one datalogger/transmitter to record all their variables of interest. This may especially be a helpful option for well-funded projects on large animals. Integrating several technologies in this way could further be improved with universal telemetry data formatting.

Temperature-sensing telemetry

Current status

Temperature can currently be incorporated into wildlife telemetry as a variable measured by the telemetry system and recorded on a separate data logger, and devices may be attached to or implanted into animals. The most common method that manufacturers use to introduce temperature sensors into a telemetry system is to create acoustic transmitters with a signal pulse rate calibrated against temperature measurements, such that the interpulse interval of the telemetry signals of field-active animals can be recorded over time, usually by a receiver, and then later converted to temperature data. Surgically implanted transmitters facilitate the collection of internal body temperature data of free-ranging animals [3, 5], allowing researchers to study the relationship between body temperature and various physiological processes and behavioral habits in a natural, ecologically relevant setting. Externally attached transmitters can yield estimates of animal body surface temperature [5, 6]. Alternatively, temperature-sensing telemetry devices may be used to outfit wild animals as "bioprobes", to record data about environments humans have difficulty accessing [35].

We found that most survey respondents do not use temperature-sensing telemetry, which explains why companies perceive a low demand for it. The application of temperature-sensing telemetry has previously been limited to niche studies on ectotherms, whose physiology, movement, and behavior are directly linked to temperature [5, 6, 36–38]. In accordance with this idea, survey respondents who reported studying ectotherms were significantly more likely to have used temperature-sensing telemetry than those studying endotherms, with use of this technology particularly prevalent in studies on sharks and rays, reptiles, amphibians, and invertebrates.

It may seem that collecting internal or surface temperature data is not as applicable to studies on endotherms, which also typically maintain relatively stable body temperatures, known as homeothermy. However, endothermy and homeothermy do not disconnect animals from the physiological, ecological, and behavioral effects of temperature [39]. Some researchers using externally attached transmitters like radio-collars to study endotherms may benefit from adding temperature sensors to their transmitters, as data on the ambient temperature of the animal's microhabitat may be useful to remotely estimate activity patterns [7]. For example, the temperature fluctuations detected by a temperature-sensing transmitter on a small mammal as it moves to and from its burrow could allow researchers to remotely construct activity budgets for the species [40]. For large animals, this may be more easily recorded using small temperature dataloggers (e.g., HOBO Tidbit, Thermochron iButton) in combination with regular, non-temperature-sensing transmitters. As reported by our survey respondents, using several pieces of equipment in this way is a common solution. However, for small animals, adding temperature sensitivity to the transmitter may be more efficient because it adds less weight than would adding a separate datalogger. Temperature-sensing transmitters implanted internally in endotherms may elucidate partial ectothermy [41] or be used to track feeding effects [42], health [43, 44], and thermal stress due to climate change [45]. Temperature-sensing telemetry may be especially helpful when studying species with regional or temporal heterothermy [46–49]. There is literature discussing the merits and potential methods to implement temperature-sensing telemetry and biologging in endotherms [50, 51], yet such applications are severely lacking.

Another reason for the relatively low reported use of temperature-sensing telemetry is that researchers are unlikely to use this technology unless their research goals explicitly include studying the thermal ecology of the study species. Temperature-sensing transmitters incur additional costs to the price, weight, size, and/or battery life of the transmitter. Most temperature-sensing transmitters, whether internal or external, send temperature measurements to a receiver and do not store the data. Researchers can log the temperature of the animal when they track them in the field, but this point-sampling leads to temporally biased body temperature data [3]. For researchers aiming to collect continuous body temperature, they can build their own data storage systems [52] or invest in a manufacturer-produced receiver and antenna array with data acquisition (e.g., Telonics or Lotek both produce such systems). Although these systems can facilitate continuous body temperature data that are very valuable for many studies, these options can also be expensive and suffer from several serious limitations, including that study animals must remain within the range of the stationary array, and that the array can be damaged by livestock, wildlife, bad weather, or people. Further information on specific challenges and solutions to measuring and logging body temperature in free-ranging ectotherms can be found in [5]. These deterrents as well as the lack of modernization of equipment likely contribute to researchers' avoidance of temperature-sensing telemetry unless they are specifically interested in temperature. As thermal studies increase to study the effects of climate change, we expect increased demand for improvements of temperature-sensing telemetry products.

Future possibilities

Most animals, ectotherms and endotherms alike, suffer in extreme heat. As climate change brings increasingly hot summers along with intermittent heat waves, collecting temperature data has become informative for more researchers studying animals in all habitats. Studies that track temperature-related habitat use inform conservation efforts to provide thermal refugia [6]. Understanding thermal preferences and limitations and predicting how animals will struggle physiologically due to climate change are important considerations now so that conservation mitigation can be optimally guided going forward.

There is incredible potential for improved temperature-sensing telemetry to promote research in physiology, ecology, and conservation. For the survey respondents that reported using temperature-sensing telemetry, there was overwhelming agreement that researchers would be willing to pay more for temperature-sensing technology that incorporated more of their fantasy equipment characteristics (Q19, Fig. 4), yet equipment manufacturers do not feel the pressure to improve or create these products. What is lacking? Some survey responses revealed that researchers are seemingly unaware of currently available temperature-sensing telemetry equipment, which could explain the lack of demand companies reported as the primary reason for their lack of investment in temperature-sensing telemetry technology. Just as the implementation of telemetry in general exploded as it became more visible, perhaps temperature-sensing telemetry needs more publicity. As soon as awareness and implementation of temperature-sensing telemetry increases, costs to both users and manufacturers will go down, but there must be better and easier-to-use temperature-sensing technology for it to expand its use among the research community. Once temperature-sensing telemetry equipment overcomes the current technological, developmental, and accessibility hurdles, a whole new realm of scientific questions will become possible. Studies that

seek to understand thermal ecology and physiology and the effects of climate change have already become more feasible with the advent of temperature-sensing telemetry, and further innovation would in turn expand the potential questions that researchers may attempt to answer.

Conclusions

Telemetry has facilitated a robust and growing field of wildlife research, which survey responses show can be used to answer a breadth of scientific research questions. However, researchers have a lengthy and ever-growing list of technological advances awaiting fulfillment by manufacturers. As manufacturers respond to researchers' demands for new and improved products, the breadth of potential telemetry studies will widen and gain depth as well. One useful telemetry application is the integration of thermal sensors, which may inform how the climate crisis is affecting animals' behavior, physiology, ecology, and much more. Given the current progression of climate change, increased application and improvement of temperature-sensing telemetry equipment is especially urgent.

A primary obstacle to telemetry innovation and implementation is funding. The future of telemetry is in cooperative use of devices and government funding for the development of new and improved products. For example, two research teams using telemetry in opposite seasons could share devices. Increased government funding for telemetry product development could help companies overcome the initial costs deterring them from making new products, especially ones that would be widely used once engineered. In conjunction, these strategies could increase the number of researchers using telemetry as well as the range and quality of technology available for their use.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40317-021-00252-0.

Additional file 1. Microsoft Forms survey sent to researchers. Documentation of the questions researchers answered as part of the survey we distributed to gauge researcher application of and satisfaction with current telemetry equipment.

Additional file 2. Survey data. Response counts and percentages for each question asked in the Microsoft Forms survey sent to researchers.

Additional file 3. Interview questions asked of telemetry company representatives. Complete list of questions asked during interviews with company representatives.

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Authors' contributions
SJW is credited for preparation and administration of the survey and interviews, analysis and visualization of the responses, and preparation of the manuscript. MFW is credited for sponsorship of this research, coordination of the studies of an endangered lizard that led to the conception of this paper, and feedback on manuscript drafts. ENT is credited for conception and preparation of the manuscript. All the authors read and approved the final manuscript.

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Availability of data and materials
The datasets created from the survey and interviews are not publicly available to maintain privacy of participants' individual responses and opinions. All analyses and figures were done in R v4.0.3. The original Microsoft Forms survey used is included with this publication as Additional file 1, and count data for the survey responses are included in Additional file 2.

Declarations

Ethics approval and consent to participate
The survey and interviews we conducted were approved by the California Polytechnic State University Institutional Review Board (Project 2020–183). All survey and interview participants were informed about the risks and benefits associated with their participation. Survey participants certified their eligibility and consent by completing and submitting the survey. Interview participants explicitly signed an informed consent form to participate and allow their responses to be included in this paper.

Consent for publication
Not applicable.

Competing interests
The authors report no competing interests.

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