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Review

Bio-logging science: sensing beyond the boundaries

Ian L. Boyd[1]*, Akiko Kato[2] and Yan Ropert-Coudert[2]

[1]*Sea Mammal Research Unit, Gatty Marine Laboratory, University of St Andrews, St Andrews KY16 8LB, UK (*ilb@st-andrews.ac.uk)*
[2]*National Institute of Polar Research, Kaga 1-chome, Itabashi-ku, Tokyo 173-8515*

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Abstract: Bio-logging has emerged as a tool in animal biology much as genomics has emerged as a tool in the study of cellular and organ function. Bio-logging is certain to increase in its importance and to influence the way we study events and processes that are beyond the usual boundaries of perception and that are remote from the observer. It is providing insights into the behaviour and function of organisms in environments that are hostile to the observer and in natural situations. In terms of the way that data are collected it has much in common with remote sensing and Earth observation. This includes *post hoc* analysis and interpretation of extensive data sets involving a low diversity of measured variables. Owing to the sparseness of data sets, practitioners need to develop better methods of applying the data to models of the organisms being studied. Although increasing technological sophistication is leading to collection of a greater diversity of variables, this also brings complications of interpreting multi-dimension data sets. It appears that technology currently constrains the type of biological questions that can be addressed but there is a danger that technological advancement could result in a loss of focus on hypothesis testing. There is evidence that the discipline of bio-logging is developing a substructure within which specialist teams of modellers, theoretical and field biologists, and engineers collaborate to address complex biological questions.

key words: bio-technology, ecology, informatics, bio-logging, physiology

Introduction

It is not the facts that are of chief importance, but the light thrown upon them, the meaning in which they are dressed, the conclusions which are drawn from them, and the judgements delivered upon them. This quotation from Mark Twain perhaps sums up what science is about. In more modern and more precise terms, we would see this as the hypothetico-reductive process that characterises the philosophy of scientific investigation. An appreciation of what Mark Twain was saying is more important today then ever before. Modern science is dominated by instruments that churn out data, the facts in the context of Mark Twain's view. There is a danger that modern science will lose sight of the ultimate goal of hypothesis testing for the sake of gathering ever larger amounts of data. The symposium on "bio-logging science" held at the National Institute of Polar Research in Tokyo during March 2003 was an opportunity to display and review a new and emerging field of science. Like the emergence of "computer science" in the 1960s, "bio-logging science" is set to revolutionise our understanding of animal biology but it also carries with it the danger of information overload and a loss of focus on genuine hypothesis testing.

Genomics emerged out of the pivotal discovery of the structure of the genetic code and led to a revolution in how we view biology. Now that the human genome has been described, as well as the genomes of several other representative organisms, we are entering the post-genomics era when the arrow of progress has to point towards higher order processes rather than the lower order basic genetic information. The reintegration of gene expression into the operations of whole organisms presents enormous challenges. Moreover, these challenges cannot be met by applying simple reductive experimental design and hoping that this will tell us about how to scale up from genes to individuals and then to populations. We need to find ways of studying the integrated effects of genes across whole organisms. Individuals are only as effective as their phenotype allows within particular environmental constraints and we know from behavioural and physiological ecology that organisms have varying environmental tolerances. Knowing what those tolerances are can tell us much about the fitness of organisms in different environments.

The problem being addressed by bio-logging science is how to measure those tolerances in the natural setting. Although we are concerned here mainly with animals, the basic concepts apply equally to plants. It is one thing to examine how a fish will respond physiologically to changes in temperature but it is quite another to understand how the fish integrates this with its behaviour and life-history to produce a strategy for survival. It would be hopeless if, for example, the fish adapts to low temperatures by the expression of anti-freeze proteins but does not also compensate for its increased vulnerability to predation as a result of its sluggishness at low temperature. The survival strategy is the culmination of gene expression not only for anti-freeze proteins but also for its toxic response to temperature and its "expectation" that conditions will change again in future. Here, "expectation" can be encoded within proteins that act as hormones or internal molecular clocks, that modulated life-history events such as reproduction, in response to an array of environmental stimuli or in relation to time itself.

The integration of these processes involves the study of complexity. The use of multivariate statistics in biology has been a first step into the field of complexity. This is where one uses a statistical model to disaggregate the variance in one high-order variable that is caused by variation in a number of lower-order variables. While the statistics of complexity may have some way to go, these tools are essential for making progress in integrative biology. Of equal importance, however, is the process of obtaining the lower-order information from organisms that can be used to examine how responses of many different types integrate to produce a survival strategy. Bio-logging science involves the measurement of these lower-order processes.

A definition of bio-logging science might be "investigation of phenomena in or around free-ranging organisms that are beyond the boundary of our visibility or experience". In this paper, we will examine the extent to which bio-logging has begun to contribute to scientific investigations.

Types of boundaries

By this definition, we view bio-logging as a process of sensing and measuring what cannot be perceived by conventional means. It cannot be seen because a boundary exists between our normal perception and sensory capabilities and the phenomenon of interest. There are several clear barriers that stand in the way of the study of organisms. One includes the body surface itself but others are spatial and temporal separation from the observer and physical barriers, including the ocean surface and the surface of the lithosphere. Sensing beyond these boundaries has strong parallels with sensing non-biological variables on spacecraft or in tethered or untethered remotely operated vehicles. A further boundary, which is neither physical, temporal nor spatial is the context in which the animal is operating. Organisms are often affected by the presence of an experimenter, experimental apparatus or by being removed from their chosen surroundings. Bio-logging allows the possibility that this type of boundary can be reduced or even excluded although the effects of bio-loggers themselves is always a subject of controversy.

Applications in the marine environment

Bio-logging has developed rapidly in the context of understanding the biology of animals in the marine environment (Kooyman, 2004) and it is worth asking why bio-logging is proceeding faster in this area of science than perhaps in any other. In this case, the boundary involves the ocean surface as well as spatial and temporal separation from the observer. There may also be a body surface boundary involved when sensing takes place within animals operating within the oceans. This is a challenging set of circumstances and, if we are to be able to understand how these animals function and interact with their environment in a way that ensures our knowledge of them is as complete as that of individuals in the terrestrial environment, then we need new methods of observation. There are, therefore, no alternatives in these circumstances. Biologists are constrained by their circumstances and this is illustrated by the rapid progress there has been in making observations of marine animals in recent years that would be considered as trivial in terrestrial equivalents. The simple questions, “where do animals go?” and “what is their behaviour?” can often be answered by relatively simple direct observation in the terrestrial environment but these types of questions have never been easy to answer in the marine environment. Bio-loggers are beginning to provide the means to investigate these types of questions.

Moreover, there are important reasons for wanting this information. Global environmental change or anthropogenic use of marine environments could affect these organisms in ways that may undermine their future viability by, for example, restricting access to critical habitat or by causing populations to decline. Thus, many of these animals present unique problems for conservation. To date, many of the marine organisms studied have been the large body-sized predators. By virtue of their position at the top of food chains these animals could be potential indicators of the structure and function of marine ecosystems (Croxall *et al.*, 1985; Murphy, 1995). The fact that bio-logging has not yet extended to lower levels of the marine food chain is reflective of the technical difficulties associated with undertaking this type of research rather than the need to do such work. The fact that the number of bio-logging studies on fish has increased over the past ten years indicates that we are progressing in the understanding of these lower levels in marine food chains.

Spreading to terrestrial environments

Although the majority of the biological models presented during the symposium were marine animals, the importance of being able to track the foraging activity of wild boars, *Sus scrofa scrofa* (Baubet *et al*., 2004) and domestic cats *Felis catus* (Watanabe *et al*., 2003) were also described. Although the tracking of terrestrial individuals may not intuitively appear as constraining as that of marine individuals, it remains extremely difficult to adapt scientific protocols to animals moving freely in dense forests, bushes, deserts or that simply migrate over appreciable distances. Many of the bio-logging techniques have equally important applications in terrestrial and marine contexts although the use of VHF telemetry for the transmission of information is much more developed in terrestrial than marine contexts. This mainly reflects the barrier to transmission of radio waves presented by seawater.

Data loggers are common tools in agricultural science and this application of bio-logging may be even more developed than in marine environments. A large proportion of terrestrial bio-logging studies are performed on captive or semi-captive animals (see review in Amlaner and MacDonald, 1980; Coates and Pennings, 2000).

Key questions

Based upon the presentations within the symposium, there are a number of central questions which the field of bio-logging can begin to address. In summary, these are: "What are the physiological and morphological constraints on behaviour and ecology?" Here we are dealing with the sensing of physiological variables, such as heart rate and temperature, within the body of free-ranging organisms. Although morphology can change with time and is an important variable, in general, morphological features are not considered to be sufficiently dynamic to require measurement by bio-loggers (but this could change if loggers capable of deployment throughout an animal's lifetime become available). However, without this capability, it is often difficult to understand the intrinsic features of organisms that constrain their distributions and abundances. Although these features have been traditionally examined in animals kept in captivity, it is increasingly clear that measurement in isolation under controlled conditions can only provide a part of the story and at some point the measurements have to be made *in situ* in freely ranging animals. These are exemplified by the experiments conducted on semi-free-ranging emperor penguins *Aptenodytes forsterii* at the "isolated dive hole" in the Ross Sea, Antarctica (Ponganis *et al*., 2004). The use of ice holes as a half-way house between free-ranging and captive experiments was pioneered using Weddell seals by Kooyman (1985) and it has proved to be a vitally important technique both for investigating questions of diving physiology and behaviour but also as a proving ground for new technology.

Progress with addressing this question has generally been very successful. Not only can field studies be supported by laboratory experiments, the physiological responses of organisms tend to be more consistent among individuals than behavioural responses which means that bio-logging from relatively small samples of individuals has the statistical power to detect changes in response to changing environmental stress. Bio-logging is the measurement of the dynamics of physical variables. Thus it is possible to measure heart rate from the detection of ECGs (*e.g.* Kuroki *et al.*, 1999) whereas the measurement of diving behaviour includes the combined detection and *post-hoc* integration of a suite of variables including hydrostatic pressure, acceleration, orientation and speed. Fat deposition in seals may also be measured by clever interpretation of their movement patterns (Biuw *et al.*, 2003). A further consequence of many of these studies is that, based on similar anatomical features among species, it is often possible to infer that physiological characteristics of one species are also likely to be found in others.

Physiological measurement was probably the first area in which bio-logging excelled, mainly in association with the studies of Weddell seals (Kooyman, 1985), and remarkable progress continues in this field exemplified by implantable data loggers with lifetimes of several months and even >1 year (Butler *et al.*, 1998).

"How do animals use space and time to maximize fitness?"

The dimensions of space and time are normally absent or much reduced in experiments on captive animals and it is these specific dimensions that can be logged. Within the constraints of behaviour and morphology, animals may choose optimal paths through space and time that maximize their lifetime fitness. While tracking animals for whole lifetimes is not yet feasible, bio-logging provides the capability to track these paths for periods of days to months, covering for instance the whole post-fledgling period in birds. (Kooyman *et al.*, 1996). There have also been long-term deployments of bio-loggers on fish (Metcalfe and Arnold, 1997).

Testing the hypotheses developed under this question has been helped greatly by the early development of time-depth recorder technology representing small, robust and easily used data loggers collecting a set of simple measurements (*e.g.* Naito, 1997; Wilson and Bain, 1984; Wilson and Wilson, 1988). These have subsequently spawned a variety of new types of instruments including satellite tags (Jouventin and Weimerskirch, 1990; Ferraroli *et al.*, 2003; Hays *et al.*, 2001), pop-up tags (Block *et al.*, 1998), geolocators (Hill, 1994; Wilson *et al.*, 1992; Afanasyev, 2004; Ekstrom, 2004) and technologies using the Global Positioning System (GPS, Steiner *et al.*, 2000; Weimerskirch *et al.*, 2002; Fukuda *et al.*, 2004; Grémillet *et al.*, 2004). Some of these instruments have been developed to relatively high levels of technical sophistication, most especially in the way in which data are compressed for transmission or storage. As a result, researchers using these types of bio-loggers have become skilled at summarizing multidimensional data in order to recreate the movements of individuals (*e.g.* Mitani *et al.*, 2003). However, there has been less progress with the interpretation of these movements in terms of animal fitness. There is a general lack of a theoretical foundation for much of this research and the big challenge for the future is to characterize the prey field of these animals in order that their movements can be studied within the context of hunting behaviour.

"How do changes in state affect an animal's decisions?"

During optimal space-time paths, animals must make decisions about, for example, where to feed, what to feed on, when to breed and how much to invest in offspring. Bio-logging has the potential to allow us to measure the changes in the state of animals and to examine the decisions made when presented with different environmental challenges.

There would appear to be considerable amounts of data available to help test hypotheses related to this question but, to date, there has been relatively little intellectual effort applied to this type of problem (but see Weimerskirch, 2003; Benvenuti and Dall'Antonia, 2004). It may be possible to develop experimental approaches to examining this question using the judicious selection of individuals representing different states or by experimental manipulation of the state of individuals (*e.g.* Kacelnik and Cuthill, 1990). There is a good background in foraging theory to provide a theoretical foundation and more use could be made of this to help design critical experiments.

"How can we use animals as indicators of environmental state?"

The final question is associated with using animals as vehicles to carry sensors that can measure the state of the environment (Furness and Nettleship, 1990; Bost and Le Maho, 1993; Wilson *et al.*, 2002). This might include the availability of food (Block, 2003; Grémillet *et al.*, 2003; Hooker and Boyd, 2003) but it could equally be the physical features of the water column in which an animal is swimming (Block *et al.*, 2001; Georges and Guinet, 2003; Fedak, 2004). This question addresses both high and low frequency processes in the environment. High frequency processes include changes in the physical features of the water column (Daunt *et al.*, 2003) whereas the low frequency process include long-term changes in ecosystem structure indicated by interannual changes in the behaviour or breeding performance of animals (Bost *et al.*, 2003). High frequency processes conform to our traditional view of bio-logging using instruments sampling at temporal scales of >1 Hz to *ca.* 0.1 Hz. Measurement of low frequency processes is also a beneficiary of bio-logging as a result of pooling across high frequency measurements through time and among different individuals.

This area of bio-logging science has the greatest potential for integration with oceanography and also to offer indices of ecosystem variability. The measurement and integration of suites of variables from animals can provide indices for use in ecosystem management (Bradshaw *et al.*, 2003). Nevertheless, at all scales, much research is required to calibrate and validate the bio-logged measurements of environmental state.

While it may also be important to be able to measure environmental state in areas not occupied by the animal, the context in which the environment is presented to an animal will affect the animal's decisions and this will, in turn, influence the life-history. These animals also have to exist within environments that conform to the envelope of physiological and morphological constraints. Therefore, the generic questions addressed above should not be viewed in isolation from one another. Rather, they are an integrated set. Bio-logging provides the technical capability to test hypotheses under this range of general questions. With these general questions in mind, the following section will examine the strengths, weaknesses, opportunities and threats associated with bio-logging as a scientific method.

Strengths

A significant strength of bio-logging is built upon what we have already identified as one of its potential weaknesses. This is the capability of bio-loggers to collect increasing amounts of data from multiple sensors at increasing levels of accuracy and precision. This has led to the accumulation of large data sets which have been difficult to analyse but, if properly curated, these data sets represent an important resource that can be used to test hypotheses generated under the questions given above. This approach to science, where data collection is distinguished from hypothesis testing can be frowned upon by a research community that may be more accustomed to testing each hypothesis in a separate experiment. However, bio-logged often employs a different approach involving *post-hoc* fitting of data to models. This approach is similar to the use of remotely-sensed data like that involved in earth observation or from space probes.

Bio-logging also allows access to non-ideal animals. This includes animals that are either difficult or impossible to study under controlled captive or semi-captive conditions. Therefore, it permits the net of knowledge to be expanded to a wider range of species and potential phenomena. It also increases accessibility to studies of animals that occupy otherwise hostile environments. The deep oceans or polar environments are logistically difficult, and expensive environments in which to study animals. Bio-logging reduces the costs of looking across these boundaries. Bio-logging still has major challenges in the study of non-ideal animals. These include extremely small, fragile, sensitive or threatened species, as well as species that are permanently inaccessible.

The memory capacity of bio-loggers and their transducer types and capabilities is improving constantly. This opens the possibility of developing increasingly sophisticated views of the biology of the animals concerned because of the simultaneous measurement of several variables, more sophisticated on-board data processing and added functionality of instruments brought about by the use of artificial intelligence. This emphasizes one of the most appreciated qualities of bio-loggers which could be described as the "wow" factor. The results of looking across boundaries can sometimes be surprising and can result in paradigm shifts in our understanding of the lives of these animals. Examples include the extreme migration distances of some species like turtles (Hays *et al*., 2001) and tuna (Block, 2003) or diving depths and durations of marine mammals and seabirds (Kooyman, 1989; Boyd and Croxall, 1996). These insights into previously unseen features of the biological world are often easily understood by, and transmitted to, the public and can raise the profile of the environmental sciences in general. The ultimate result of engaging the attention of the public is that the process leads to empowerment of the public to make informed decisions and bio-logging has an important part to play in this in future.

Weaknesses

One of the commonest criticisms we have heard of bio-logging science is that it is a field led by technology. While technology is undeniably a major driver of progress, we suggest that, rather than being led by technology, bio-logging science is actually limited by technology. The physical size of instruments and sensor limitations as well as systems for the attachment or implantation of instruments are all limiting in terms of the hypotheses that can be generated.

Nevertheless, the weakness brought about by technological limitations needs to be addressed by means other than simply developing more sophisticated instruments. While data sets may be increasing to a size that renders them almost unmanageable, these normally cover relatively few variables. They also tend to cover rather short durations in the life-histories of individuals. Relative to the demands of some of the hypotheses generated under the questions raised above, the data sets being generated are sparse. To counteract this some lessons could be learned from oceanographers who have become skilled at using sparse data and have built sophisticated circulation models to interpolate between the data that are available. Therefore, where marine predators are concerned, new initiatives in life-history and foraging modeling could be useful and too little attention may have been given to the development of these models in parallel with the development of new technology. It is inevitable that bio-logging science will be being led by technology unless the technology developments are prioritized according to hypotheses.

The lack of the insights from modeling could also have led to a further weakness in the current bio-logging research. Intuitively, we think in terms of space and time dimensions partly because these are the easiest to measure but increasingly we are viewing the life-histories of animals from the perspective of other dimensions that are broadly termed the animal's state (*e.g.* fatness, reproductive condition, social status). Important decisions made in an animal's life are less likely to depend upon where an animal is in space, or how old it is, than on its current state. Of course, location in space and time are state variables in their own right but they may explain relatively little of the variance in the behaviour of an animal. Energetic state and the animal's perception of risk within its environment are likely to be much more influential. There has been a tendency, therefore, to concentrate upon the space and time dimensions as the independent variables in behaviour rather than to see these as two perhaps rather weak states within a range of state variables. This has perhaps led to reduced pressure to develop technologies that will measure other forms of state, including energy reserves.

One of these state variables that has been extremely difficult to measure and that is largely ignored is the social environment of animals. We usually assume, from a statistical viewpoint, each individual that carries an instrument is an independent unit of measurement and yet we know by observation that this is not true for many species (*e.g.* Tremblay and Cherel, 1999). Bio-logging has yet to crack the problem of measuring social interaction. Preliminary steps in that directions were presented at the occasion of the bio-logging symposium. For instance, intra- and interspecific communication in cetaceans could be studied using acoustic tags (Akamatsu, 2003; Akamatsu *et al.*, 2000) while video cameras could bring substantial progress to our understanding of the social behaviour of seabird or seal communities (Marshall, 1998; Hooker and Boyd, 2003; Y. Naito, pers. obs.).

Opportunities

Some of the opportunities for bio-logging science are obvious. Bio-logging has made good use of advances in microelectronics and it is clear that continued advances in this field will be exploited by developing new bio-logging techniques. This will include increased memory capacity of instruments, new methods for transmitting data at higher rates, new and better sensors and components with lower power consumptions. But bio-logging, especially in the biomedical field, could probably have greater influence upon other emerging technologies, such as nanotechnology and there may be opportunities to become involved in the development of new power sources that could result in unlimited deployment durations (Muramoto *et al.*, 2004).

There is also an opportunity to improve what is already done well. Current capabilities are already substantial but reduction in cost could result in deployments of instruments in situations where the risk of recovering data is relatively high. This could increase opportunities to investigate a range of species which are relatively inaccessible to researchers. On the same theme, there is an opportunity to make better use of the data already collected. Improved dissemination of data through data grids could maximize the return on investments in data collection and this may require revised attitudes to data ownership. Such a view of data collected as a result of disturbing animals may also be ethically desirable.

A revised attitude to data accessibility is a precursor for making best use of opportunities for inter-disciplinary integration of bio-logging studies with those from other disciplines. In the case of marine predators, links with the oceanographic community are likely to prove to be fruitful and beneficial to both groups.

There are new opportunities for the commercialisation of the technology produced. Commercialisation can be a double-edged sword. While it is the most effective way of making sure that instruments can be distributed to a wide range of possible users, and it can help to generate income for investment to maintain the process of developing new bio-loggers, it is probably not the most effective route for the development of new leading-edge solutions. The close juxtaposition of the researchers who use the technologies, and who are a fertile source of new ideas, and those who are undertaking the technical developments would appear to be the optimum combination. Consequently, opportunities for commercialization will only pay off if this close relationship can be maintained.

Threats

Technology commercialization can, therefore, also be seen as a threat to progress because it could lead to directing the emphasis towards technically feasible solutions that have a commercial future rather than those that have been developed to test hypotheses. This may be one reason for the narrow range of capabilities in bio-loggers currently on the market, at least relative to what is possible in terms of capability. While it is clearly in the interests of commercial producers to satisfy customer's needs, there will always be a trade-off between the need to generate revenue by addressing the needs of the widest possible market and the production of innovative one-off designs. Too much emphasis on commercialization could, therefore, be a threat to progress. Other threats come in the form of technological barriers. There will always be limits of size and power beyond which technological innovation cannot go, but bio-logging needs to meet the challenge of studying smaller-scale processes.

However, perhaps the greatest threat to the field comes from ethical arguments. Bio-logging interferes with the normal lives of animals and, while it is rarely in the interest of the science being studied to cause changes in an animal's behaviour principally because of the bio-loggers (Kimmich, 1980), there is an increasing concern for vigilance towards what is being done. There are extreme views amongst the public, and some scientists, about the acceptable level of disturbance resulting from scientific study. Bio-logging science provides the opportunity to permit ethical intervention in the lives of animals. The best illustration of this comes from the way in which studying marine mammals has changed. Prior to the 1980s the most feasible method of studying wild marine mammals was, in many cases, using lethal intervention. Bio-logging has contributed to the continued flow of information about marine mammals as this method of sampling has been phased out. Continued pressure to find less invasive methods of study will go on and bio-logging science must itself evolve in tune with societal concerns on ethics. The scientific community using bio-logging techniques seems to be aware of its responsibility towards the animals and the public. Numerous experiments have been conducted over the past thirty years to determine the effects of carrying devices on animal performance and fitness (Ropert-Coudert and Wilson, 2004 and references therein), resulting in the publication of several guidelines about the use and risk of abuse of bio-logging (Hawkins, 2004). Finally, it is the duty of the bio-logging community to communicate with the public and to spread the image of responsible scientists in order to correct the wrong images that people may have about 'instrumenting' animal.

Conclusions

Bio-logging science is a fast-moving field including many of the desirable features of modern science, such as inter-disciplinarity, technology application and societal relevance (Fig. 1). A remarkable variety of instruments is now available to scientists from implantable physiology loggers through to satellite transmitters with sophisticated data collection protocols and data compression routines that can send information from animals anywhere in the world. In addition to these, new and more accurate sensors are providing insights that are allowing the reconstruction of behaviour and inferences about its function. This is leading to the capacity to test increasingly sophisticated hypotheses and the high level of analysis that

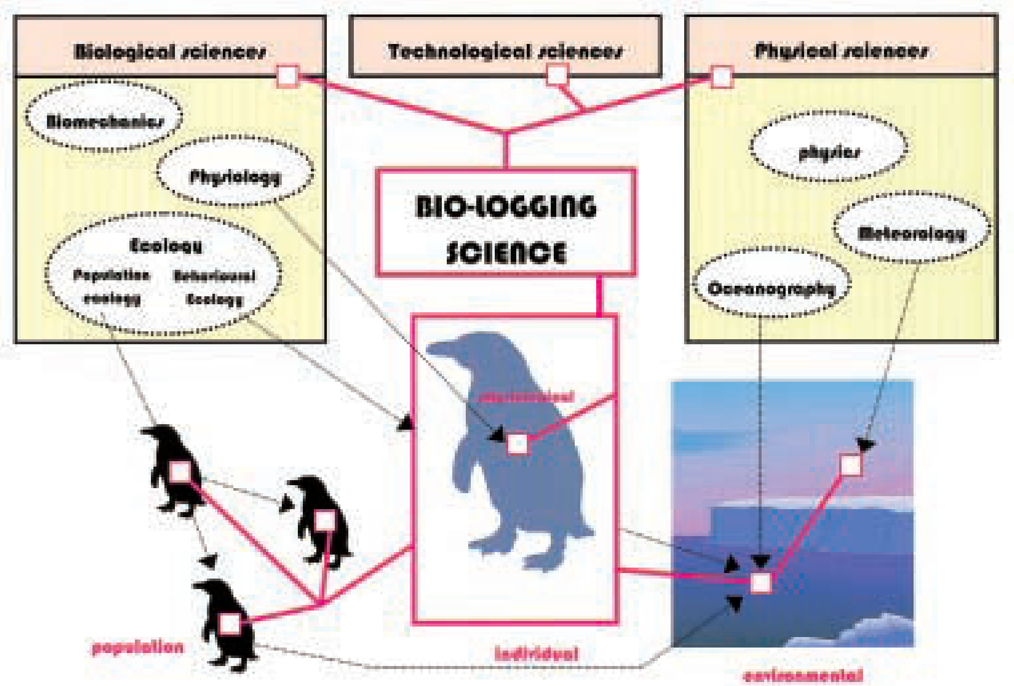

Fig. 1. Diagram representing the network of information collected through bio-logging science (red connectors) that links the individual and its functions to the environment (biotope, left, and biosphere, right). There is a similarity between the interface box that bio-logging researchers use to communicate with data loggers and bio-logging which is at the interface of a large variety of classical areas of sciences, namely biological, technological and physical sciences (yellow boxes).

is now possible, together with multidimensional presentation of the data is aiding the interpretation of complex data sets. The range of species which can be included in bio-logging studies is increasing because of a combination of reduced costs, reduced physical dimensions of instruments, greater manufacturing flexibility and an increased realization amongst researchers about the advantages of using bio-loggers as tools.

The expansion of the field is leading to increased specialization amongst researchers. No longer is it normally possible for a single person to design the experiments, construct the instruments and analyse and interpret the data. Teams of individuals with complementary expertise are required, often in trans-institutional collaborations, in order for bio-logging to continue developing rapidly. The move towards collaboration between institutions is illustrated by the development of the large-scale programs including TOPP (USA, http://www.toppcensus.org/), DSL (Japan) and NEO (Europe). As a field which is highly dependent upon technology and scarce or specialized logistics opportunities, bio-logging science has much in common with other fields of remote sensing. Increasingly, there is likely to be a division between those who collect and collate data and those who generate hypotheses then analyse and interpret those data in the context of models. This is because the data are both complex and sparse and specialists are needed to deal with each stage. There is also an increasing recognition that the data sets resulting from bio-logging have the capability of addressing multiple hypotheses and they could be viewed in much the same way as data resources from remote sensing such as Earth observation. A major challenge is to collate data in a way that makes it accessible to a community of scientists who would not normally have been involved in bio-logging studies.

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