

# Communications

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## Novel opportunities for wildlife conservation and research with real-time monitoring

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**Abstract.** The expansion of global communication networks and advances in animal-tracking technology make possible the real-time telemetry of positional data as recorded by animal-attached tracking units. When combined with continuous, algorithm-based analytical capability, unique opportunities emerge for applied ecological monitoring and wildlife conservation. We present here four broad approaches for algorithmic wildlife monitoring in real time—proximity, geofencing, movement rate, and immobility—designed to examine aspects of wildlife spatial activity and behavior not possible with conventional tracking systems. Application of these four routines to the real-time monitoring of 94 African elephants was made. We also provide details of our cloud-based monitoring system including infrastructure, data collection, and customized software for continuous tracking data analysis. We also highlight future directions of real-time collection and analysis of biological, physiological, and environmental information from wildlife to encourage further development of needed algorithms and monitoring technology. Real-time processing of remotely collected, animal biospatial data promises to open novel directions in ecological research, applied species monitoring, conservation programs, and public outreach and education.

**Key words:** *African elephants, Loxodonta africana; environmental monitoring; geofencing; geographic information systems, GIS; global positioning system, GPS; immobility; real-time monitoring; telemetry; wildlife monitoring.*

### INTRODUCTION

Real-time monitoring (RTM) of environmental data is increasingly common, advanced by the expansion of communications networks and the improvement of wireless sensor technologies. A vast number of environmental variables can now be measured, processed, disseminated, and accessed in real time and are being used in diverse applications to improve public safety and for global monitoring, including the detection of earthquakes and extreme weather events, and monitoring of climatic variables. The unique opportunities afforded by RTM are changing academic and public ability to access and interact with environmental data.

RTM is also entering the fields of animal tracking and movement ecology, providing novel research opportunities. Here we present a framework and examples by which RTM of animal movement can help advance our understanding of animal-movement ecology and behavior and also provide critical information for managerial and conservation action.

The use of remote sensors to track movements of animals has evolved from very high frequency (VHF) radio beacons to Global Navigation Satellite Systems, such as the Global Positioning System (GPS), which can be used to pinpoint, with high accuracy, the location of an animal at a given time. Technological advances—especially the miniaturization of electronics, reduced energy consumption, and extension of battery life—have greatly expanded the types of species that can be tracked and the quantity and quality of data collected (Ropert-Coudert and Wilson 2005, Wilson et al. 2008). Current analytical approaches of these high-resolution data

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provide new insight into animal life history and behavior, including definition of travel routes (Berger et al. 2006), Wall et al. (2013), spatially explicit differentiation of behaviors (Patterson et al. 2008), and novel information on energy budgets (Fryxell et al. 2004). In addition, sensor units can be configured to record covarying, exogenous environmental variables (e.g., ambient temperature, relative humidity, ambient light), and endogenous physiological information (e.g., skin temperature, heart rate) collectively referred to here as “biospatial” data.

Communications technology, either satellite-based (e.g., the “Argos,” “Iridium,” or “Inmarsat” constellations) or the ground-based global system for mobile communications (GSM) technologies, can now be integrated into tracking units, making it possible to track animals and process data in near real time (Dettki et al. 2004, Urbano et al. 2010). Here we define *real time* to refer to any data that are immediately telemetered upon acquisition and readied for analysis within a period of five minutes. RTM has enormous potential in the fields of wildlife ecology and conservation, especially for at-risk wildlife, e.g., from poaching (Wittemyer et al. 2011), or wildlife prone to frequent interactions with humans (e.g., mountain lion incursion into residential areas; Kertson et al. 2011), or for studies requiring immediate data retrieval (e.g., prey/predation interactions; Knopff et al. 2009).

RTM analysis allows an analyst to visualize the position or movement trajectory of an animal within a geographic information system (GIS) as it unfolds. Such real-time interaction with animal movements can help alleviate the disassociation between ecologists and their study subject when remotely collecting tracking data, allowing development of a biological “feel” for the behaviors of tracked individuals (Hebblewhite and Haydon 2010). Desktop or mobile software programs, such as Environmental Systems Research Institute (ESRI) software or Google Earth can act as wildlife observatories in the absence of continuous field observation, including visualization of the topographic and ecological context in which the movements take place with the addition of layers of geographic information (e.g., high-spatial-resolution satellite imagery or land-use coverage). Direct application of real-time visualization can greatly enhance patrolling focused on at-risk species or access to cryptic organisms. To augment such visualization and interpretation, we propose several continuous algorithmic analyses that can serve to identify quantifiable behaviors of interest across numerous individuals and different temporal and spatial scales.

In this paper we present approaches that leverage developing algorithmic spatial informatics with real-time tracking data to expand the applications and insight of animal remote sensing. In particular we look at how real-time access and analysis of movement data can be used to answer questions relevant to both wildlife ecology and conservation research, e.g., “What is the

current location of an animal?” and “What is the animal doing?” Two approaches—position-based and movement-behavior-based analyses—can be used to answer such questions. We give examples of application of these concepts in an RTM system we have developed to study African elephants (*Loxodonta africana*). We provide detailed information on the customized software and implementation in the Appendix. Finally, we discuss developing techniques using biospatial data that address the question “What is the animal experiencing?” In combination, these real-time approaches can provide a cohesive picture as to the current spatial, behavioral, and physiological state of an animal.

#### *Positional analyses*

Determination of the current spatial relationship between an animal and geographic features—points (e.g., water holes for arid-land wildlife), linear features (e.g., roads, fence lines, fishing nets), areal features (e.g., hunting concessions for trophy wildlife), or spatially dynamic features (e.g., a mobile herd of livestock)—can provide valuable insight for conservation and management decision making and insight into ecological processes. Within the real-time monitoring framework, we suggest two positional metrics useful to wildlife management and ecological research: proximity and geographic intersection.

*Proximity.*—Proximity refers to the Euclidean distance between an animal’s location and a spatial object, and is a useful metric in a number of scenarios. For example, conspecific proximity and contact is of interest in epidemiological and evolutionary studies such as in the spread of disease (e.g., bovine brucellosis) from cattle to wildlife or vice versa (Geremia et al. 2011). Similarly, conspecific proximity could be used in monitoring specific movement-ecology processes such as inter-species proximity during grazing succession (e.g., as occurs in the Serengeti migration; Gwynne and Bell 1968). RTM proximity analysis could also be applied to situations where certain geographic points or areas pose an immediate threat to a species but where quick management action could help in protection (e.g., shutting down energy wind turbines for migrating bats; Kunz et al. 2007, Willis et al. 2010).

*Geographic intersection.*—Where proximity can be used to assess approaches of an animal to areas of interest, geographic intersection identifies incursions into or across areas of interest. Analysis of geographic intersection is popularly termed *geofencing*—the detection of the location and timing of an animal’s path into, or across, geographic objects as represented within a GIS, such as a land-cover classification or buffers of point or linear features. Geofencing has a myriad of applications in wildlife conservation and management, including the alleviation of human–wildlife conflict, alerting humans to the presence of susceptible species, or alerts of animal presence in critical safety areas (e.g.,

whales entering shipping lanes; Ward-Geiger et al. 2005).

#### *Movement-behavior analyses*

Movement-ecology theory posits that the track of an animal may be considered a mixture of multiple, definable behaviors such as foraging, encampment, resting, fleeing predators, dispersal, and so forth, which reflect both endogenous and exogenous factors influencing the animal over its life history. A behavioral state, provided it is statistically discernible, may be inferred by comparison with empirically derived movement signatures or from transitions in state (Fryxell et al. 2008). Movement rates can be used to determine the behavioral state of an animal (Gurarie et al. 2009) while sophisticated switching state-space models (SSSM; Jonsen et al. 2007) and behavioral change point analysis (BCPA; Gurarie et al. 2009) have also been used to identify shifts from one behavioral regime to the another (e.g., a shift from foraging to resting behavior). Several behavioral states are of potential interest to wildlife ecologists and managers, two of which we believe can be highly beneficial to management and research within the real-time monitoring framework: movement rate change and immobility.

*Movement rate.*—Rate of movement and the underlying locomotive mechanical energy output can provide fundamental insight into an animal's physiological state and current behavior. Significant movement-rate reduction that results from injury, illness, or other condition such as parturition (e.g., female mule deer; Long et al. 2009), animals that are moving in a discernible pattern such as sustained increased movement demonstrated during migration or dispersal (Singh et al. 2012), or specific movement characteristics indicative of distinct behavior such as rutting (e.g., elephant "musth"; Poole and Moss 1981) or hunting (Hansen et al. 2013a), may be of specific research or management interest. Using nonparametric approaches implemented in real time allows identification of such behaviors of interest. For example, reduced or increased movements can be identified by comparing real-time telemetered movements with a distribution of movement rates for an animal collected and established when the animal was known to be operating normally (i.e., spanning a mix of different but acceptable behavioral modes). After the distribution of normal movement-rate statistics has been established, a movement-rate algorithm compares the cumulative distance traveled in the most recent available temporal window (e.g., 24 hours) to the cumulative distribution of normal activity rates. If the value falls below or above the distribution value at a demarcated percentile for the defined time scale then an alert can be raised.

*Immobility.*—Movement immobility is defined in terms of the cessation of displacement by an animal over a period of time and is a species-specific behavior. For predators, immobility over a certain period could signal a predation event and kill site (Knopff et al. 2010) or denning behavior (Ciarniello et al. 2005),

whereas for herbivores the same may signal mortality or entrapment. The incapacitation or death of an animal and the identification of kill sites are events of special importance to wildlife management, and localizing them quickly is an important objective in many species-monitoring projects (e.g., for security response to poaching or in studying predator-prey interactions). One approach to identify immobility is to search for spatial-temporal clusters in recorded positions (Knopff et al. 2009). Any group of points can be quantified in terms of the mean distance of the points from their common center of mass and the time spanned by the group. A particular grouping that has a mean value less than a critical mean radius and spans a time-period greater than a minimum time threshold can then be classified as an immobility event and an appropriate species-specific alert can be issued.

#### APPLICATION OF RTM TO AFRICAN ELEPHANTS

We are applying the four described spatiotemporal analyses of movement in a real-time monitoring (RTM) system we have developed to monitor wild African elephants in the Samburu, Laikipia, Mt. Kenya, Chyulu Hills and Mara ecosystems of Kenya and the Kruger-Limpopo ecosystem in South Africa. Global positioning system (GPS) tracking data are being collected using four collar types deployed on 94 elephants. Locations are most frequently sampled at 1-h intervals while a fewer number also report at 4-h intervals or less (Appendix: Table A2). Once a position is acquired by a GPS, it is telemetered using either a GSM or Inmarsat Satellite Communication connection depending on collar type (Appendix: Table A1).

Data are received by our Amazon Elastic Compute Cloud (EC2) cloud-based server from a collar unit using either a direct connection (e.g., via Transport Control Protocol/Internet Protocol [TCP/IP]) or retrieval from a third-party application programming interface (API). In both cases our custom-built *AnimalLink* software handles ingestion of inbound data and stores it locally in a PostgreSQL database called *AnimalTracking* (Fig. 1). Our custom-built *MovementMonitor* software monitors incoming data and implements each of the four GIS algorithms (proximity, geofencing, movement rate, immobility) on a continuous basis.

Once a behavioral state of interest has been identified algorithmically, an alert is triggered and distributed using a number of dissemination methods that target the variety of users of our system (Figs. 1 and 2), including e-mail (e.g., Appendix: Fig. A2), SMS (short-message system, limited to 160 characters; the primary choice for most practitioners in the field) or via either of our two custom-built APIs: (1) a Google Keyhole Markup Language (KML) API for use with Google Earth and (2) an ESRI API for use with ArcGIS Desktop software. The real-time distribution of alerts allow analysis and visualization of the identified behavior in central research stations, warden offices,

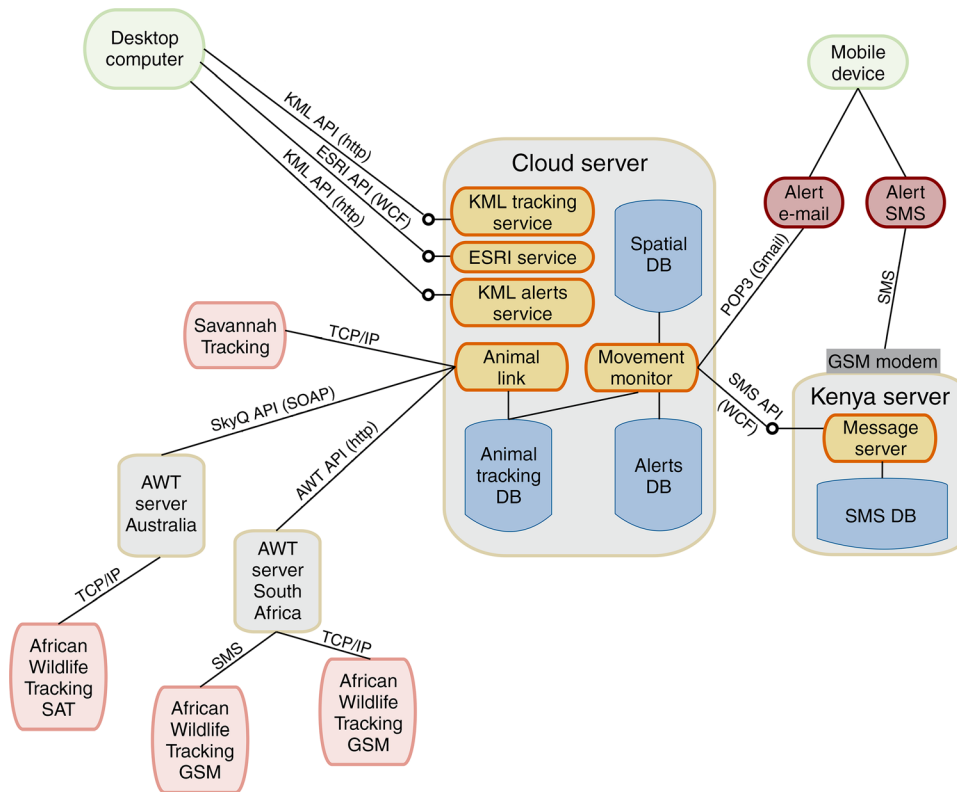


FIG. 1. Real-time monitoring (RTM) system to monitor the movement behavior of African elephants (*Loxodonta africana*). GPS tracking data are collected from four collar types deployed on 94 elephants and telemetered to a cloud-based server. Our *AnimalLink* software ingests the data and stores it in a PostgreSQL database (DB) (*AnimalTracking*). *MovementMonitor* software continuously monitors incoming data and implements four algorithms (proximity, geofencing, movement rate, immobility). If an alert condition is detected, both an SMS message (160-character limit) and e-mail are generated and issued to subscribed users. Application programming interfaces (APIs) make both alert and tracking data instantly available to desktop- and mobile-based clients including both Google (as Keyhole Markup Language, KML) and Environmental Systems Research Institute (ESRI) geographic information system (GIS) software. Full technical details of the implementation of our RTM system are provided in the Appendix. Acronyms are: AWT, African Wildlife Tracking (Pretoria, South Africa); GSM, global system for mobile communications based on telemetry; SAT, satellite-based telemetry; WCF, Windows Communication Foundation; POP-3, Post Office Protocol; and SOAP, Simple Object Access Protocol.

or visitor centers, as well as directly in the field by stakeholders and wildlife employees through portable internet-linked devices.

Our African elephant RTM system has the marked advantage of focusing on a species able to support large hardware payloads, a practical limitation in other species that may limit the current applicability of the concepts and ideas we present. While several of the algorithms are specific to elephant ecology and behavior, the principles presented are readily extendable to a multitude of species and questions contingent on the availability of species-specific RTM hardware. We provide further detailed specifications of our RTM system in the Appendix.

#### Implementation examples

The proximity algorithm is being implemented in Kenya to monitor the spatial proximity of elephants to several spatial objects of interest. One example is the A2

highway (part of the Cape-to-Cairo route) where crossing points and human–elephant interaction are of interest to wildlife managers. Alerts are issued in the event that an elephant is detected within 1 km or less of spatial features.

Geofencing was first implemented for use in problem-animal control in Kenya in 2007. The target animal was a bull elephant prone to breaking fences that made almost nightly forays (over a three week long period) through an expensive, electric fence into neighboring subsistence farming land in order to forage in fields of maize (*Zea mays*). A virtual fence line was erected corresponding to the electrified perimeter fence of the conservancy (see inset in Fig. 3A) and alerts generated by our RTM system were disseminated to wildlife managers using short message service (SMS) each time the bull broke through the actual fence line. After receiving automated alerts from the Geofence algorithm, patrol teams responded to his incursions forcefully and

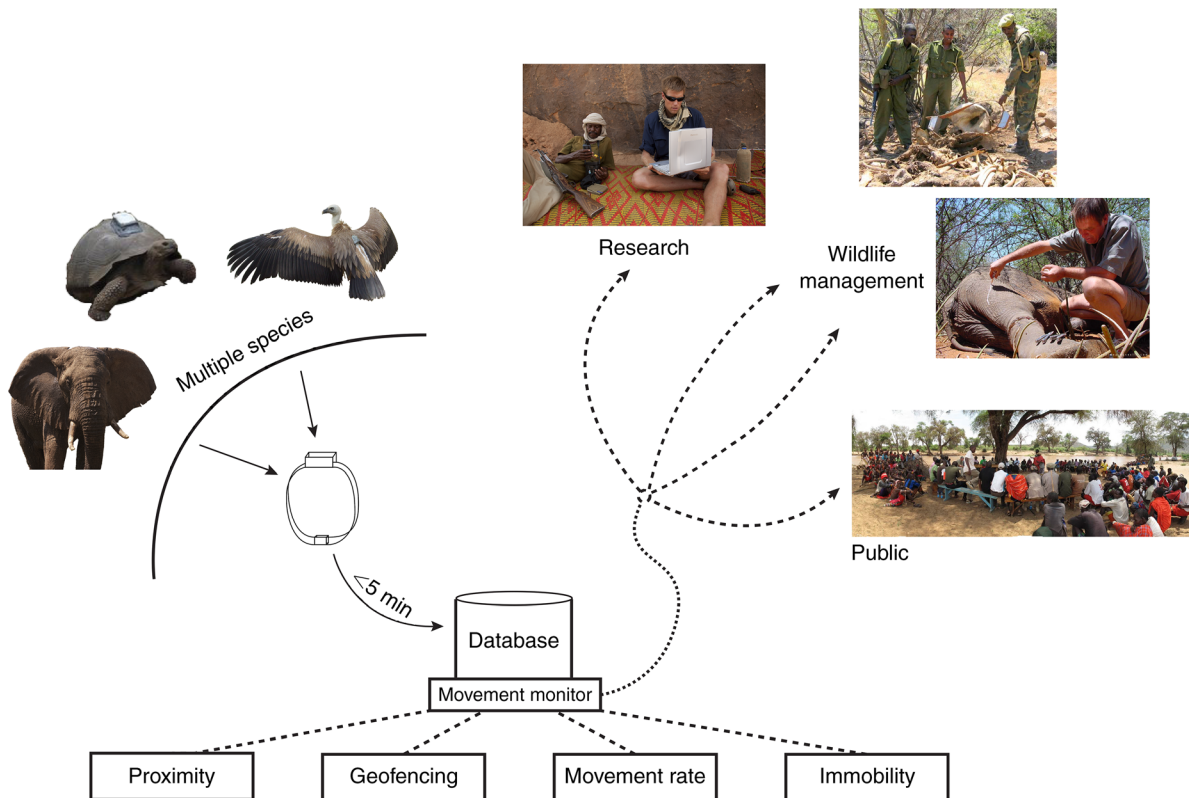


FIG. 2. Example of a RTM system for multiple wildlife species. Software is set to analyze these data with a suite of relevant algorithms (proximity, geofencing, movement rate, immobility) for a given species and to produce results within five minutes of collection. If certain conditions are met, alerts can be issued in a number of ways (e.g., SMS, e-mail) to a large audience with different needs (e.g., researchers, wildlife managers, the public). Photo credits: tortoise, Franz Kummeth; vulture, Orr Spiegel.

eventually curbed this behavior with aversive conditioning.

The utility of movement-rate analysis in the context of identifying an injured animal to allow prompt veterinary treatment is exemplified via our experience with a wounded elephant tracked in the Maasai Mara, Kenya. The cumulative movement distances traveled within successive 24-h periods was established during a two-month period when the animal was not physically injured (Fig. 4A). The algorithm then continuously monitors cumulative travel distances within a 24-h period and compares the calculated percentile value to the distribution. We used the first-percentile value of the normal movement-rate distribution as the cutoff for determining below-normal movement rates. Following two veterinary interventions, the animal recovered and movement returned to the pre-injury baseline (Fig. 4B).

Our immobility algorithm, which is similar to the agglomerative weighted centroid clustering algorithm (Legendre and Legendre 1998) used by Knopff et al. (2009), works by adding successive positions to a seed cluster of two points, recomputing the geometric center, and determining the number of points that fall within a critical threshold. All points falling within a temporal

window (e.g., 24 hours) are added to the cluster and if the probability of a cluster exceeds a threshold value (e.g., if 80% of points fall within the critical radius) then an alert is triggered. We tested the performance of our algorithm post hoc on six elephant-movement data sets where each animal had been killed by poachers but the collar unit continued to report positions post-mortality. Because elephants are stationary while they rest or sleep, we only considered immobility events that spanned a period longer than five hours (elephants typically sleep for bouts shorter than this cut-off) and that occurred within a minimum cluster radius value of 13 m. These values successfully identified the elephant mortality while minimizing the number of false positives (Appendix: Table A3), but will vary by species. Current RTM immobility monitoring is a key component of our anti-poaching and monitoring activities (Wittemyer et al. 2011).

#### FUTURE DIRECTIONS

We have shown that algorithmic implementation of tracking-data analyses can be used to effectively monitor wildlife in real time. However, measurement of variables—both physiological and environmental—concomitantly with movement data, expands the possibilities

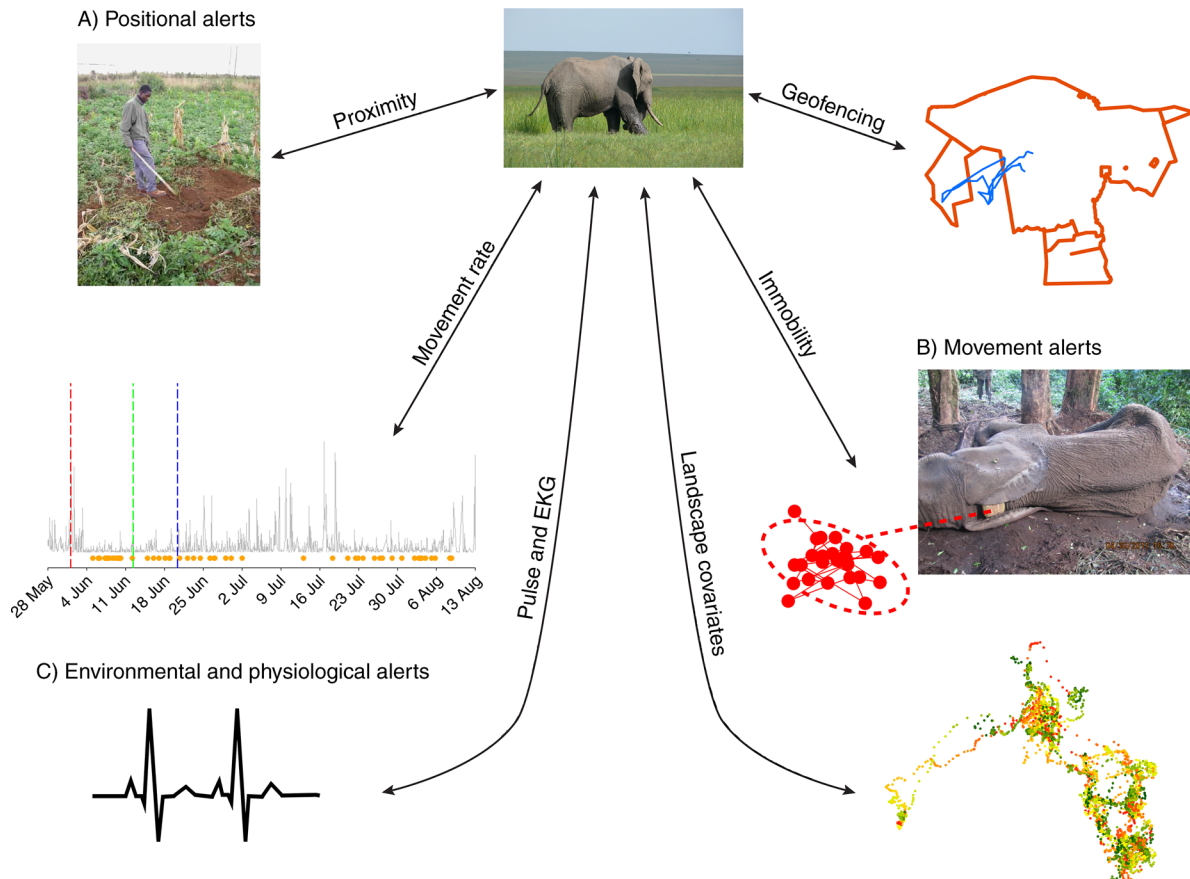


FIG. 3. Examples of the RTM algorithms that can be applied to a given wildlife species (e.g., African elephant). (A) Positional: *proximity* (e.g., the distance the elephant is from a farming area), and *geofencing* (e.g., the time and position where the elephant crossed an electric fence line). (B) Movement behavior: *movement rate* (e.g., the time and position when the elephant's 24-h cumulative distance traveled dropped below a threshold value) and *immobility* (e.g., the time and position where an elephant stopped moving for longer than 5 h). (C) Physiological and environmental: heart-rate (e.g., the time and position when the heart beat of the elephant stops) and landscape environmental covariates of interest (e.g., the time and position when the localized normalized difference vegetation index [NDVI] value reaches a threshold of interest).

associated with real-time monitoring beyond location-based inferences alone (Hebblewhite and Haydon 2010). Covariate measurements can give information as to the internal state and health of an animal, and the environmental conditions it is experiencing, providing rich ancillary data layers from which complex behavior patterns can be interpreted and the state of the animal understood. Coupling the real time algorithmic analysis of animal movements with covariate information creates an exciting new frontier in applied ecological research and we briefly discuss here several currently available technologies that would be of immediate practical application in theoretical and applied research.

#### Physiological data

Relatively simple physiological measurements, such as an animal's heart rate, can lead to a host of interesting analytical opportunities such as spatially explicit metabolism and energy-expenditure partitioning (Cooke et al. 2004). When considered in real time, physiological

information is applicable within a wildlife management and conservation framework as a way of assessing animal mortality (e.g., from poaching) or other physiological responses (e.g., stress) that would considerably improve movement-based analyses such as the aforementioned immobility-detection algorithm. For example, the ability to detect, in real time, the absence of a pulse in a wild animal, would greatly increase the capacity for management action, as in the case of illegal wildlife poaching. Telemetry of heart rate and core body temperature with movement data would mark a major research and management milestone opening avenues to remotely measure animal energetics, health, and disease spread based on physiological data.

#### Environmental data

Animal-attached sensors, at a point in time, can provide a spatially located datum of a host of environmental variables such as ambient temperature, humidity, light, background noise levels, and so forth. Great

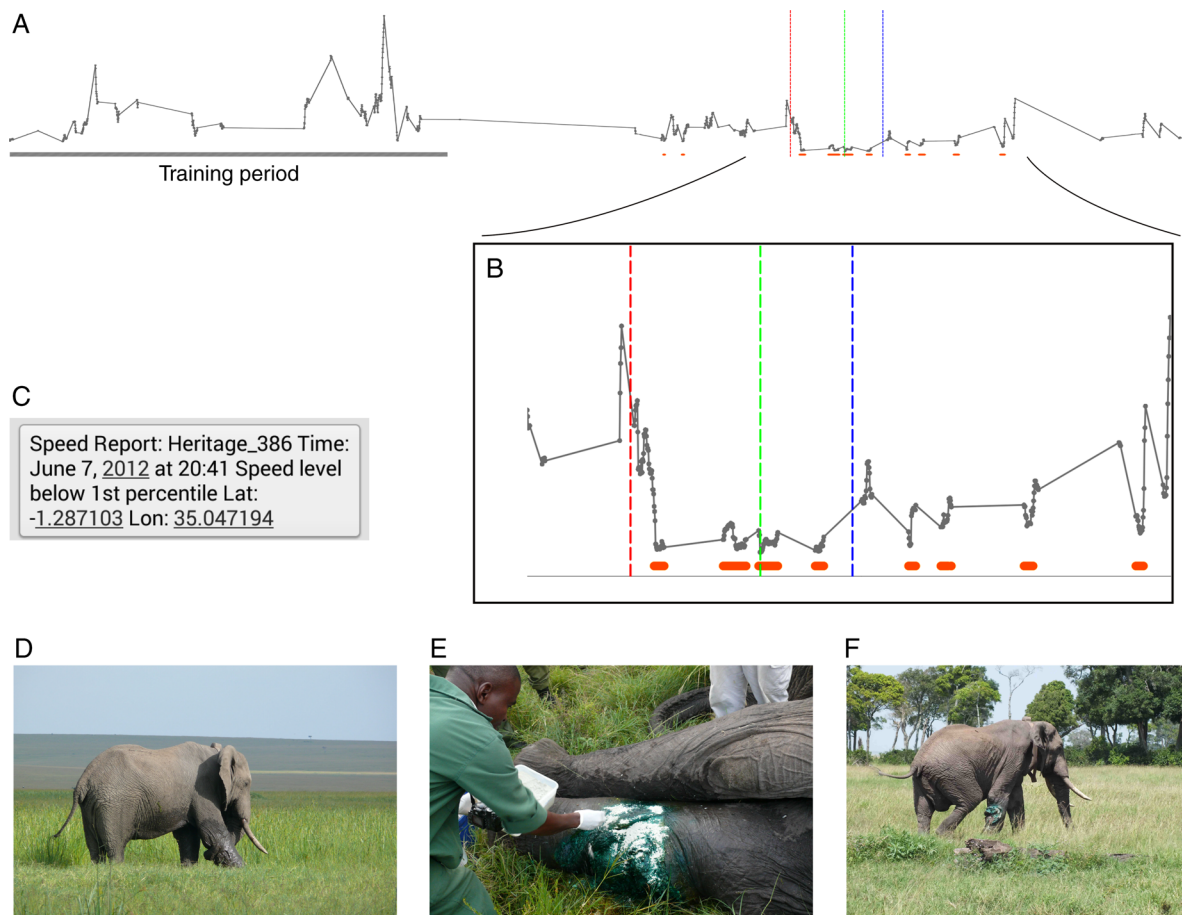


FIG. 4. Analysis of the daily rate of movement of a bull elephant in the Maasai Mara, Kenya. (A) Depiction of 24-h cumulative distances traveled based on the GPS tracking locations (nine months of data are shown). The first two months were used as a training period to develop a distribution of normal behavior. (B) Subset graph showing when the bull elephant was probably injured (vertical dashed red line), first and second treatments (green and blue vertical dashed lines, respectively), and the alerts generated by our algorithm (orange dots). Each orange dot signifies that the previous 24-h cumulative distance traveled fell below the 1% level of the distribution of daily cumulative distances traveled based on the first two months of data when the bull was known to be in good health. (C) Example of an SMS message sent by our system corresponding to each alert. (D) The injured bull before treatment. (E) The bull being treated by a Kenya Wildlife Service veterinary doctor. (F) The bull after treatment and eventually making a full recovery. Photo credits: Madeleine Goss.

potential for understanding movement behavior arises when these data are analyzed in real time, such as triggers of dispersal and migration (e.g., the movement trigger for the Mali elephant population; Wall et al. 2013).

Remotely sensed imagery products can provide a wealth of information about environmental conditions (e.g., weather, vegetation indices, and so forth) but have traditionally been slower to acquire, process, and analyze than animal-movement data (although see Urbano et al. [2010]). Recently, development of advanced cloud-based image-processing infrastructures, such as the new Google Earth Engine (GEE) technology (Hansen et al. 2013b), enables near real-time access to satellite image data products and analysis of them “on-the-fly” with an unprecedented scale of computing power. GEE technology promises many unique opportunities for ecological monitoring of wildlife.

#### Acoustic data

Acoustic monitoring systems are becoming more prevalent and have the potential to provide data useful for a variety of behavioral or ecological research areas. Successful implementation of such devices includes monitoring cattle-foraging behavior (Clapham et al. 2011), characterizing activity budgets of wildlife (Lynch et al. 2013), investigation of species communication (Payne et al. 2003), or identifying the presence of marine mammals (Klinck et al. 2012). Real-time directional tracking of sounds is also possible (Bergamo et al. 2004) and gunshot detection (e.g., “ShotSpotter,” available online)<sup>6</sup> is an immediate application of the technology

<sup>6</sup> <http://www.shotspotter.com/>

for animal conservation and management purposes where poaching is a problem.

### Accelerometry

Finally, a rapidly developing approach in animal telemetered data are applications that monitor animal activity through fine-grained sampling of overall dynamic body accelerations (ODBA) using tri-axial accelerometers (Wilson et al. 2006). The high sample rate of current instruments (e.g., 32 Hz) can serve to derive nearly continuous movement paths and are analyzable into detailed segmentation of energy expenditure (Halsey et al. 2009). The high sample rate of these units creates significant data volume in comparison to traditional movement data and has implications for real-time telemetry given the limited memory/battery life of current animal-attached tag systems. As a result, on-board processing of accelerometry signals or short recordings of ODBA will be required for real-time applications.

### Conclusion

Advancement of technology and the continued expansion of communications networks are allowing targeted, on-animal data collection and the economical and expedient distribution of such data. As a result of these developments, opportunities available to researchers and wildlife managers for studying and monitoring wildlife in real time are expanding rapidly. The movements of an animal, as recorded and relayed with a remotely attached tracking device, provide information about the animal's current spatial behavior from which reliable inferences can be made as to its condition and physical state. Processing information as it is collected can help researchers collect context-specific data needed to understand drivers of behavioral change. For more-applied objectives, such information allows managers to take timely and crucial management action. The real-time monitoring algorithms presented here for monitoring African elephants (proximity, geofencing, movement rate, and immobility) are widely adaptable and applicable to monitor a variety of behaviors across numerous species. Exciting new developments, both in attached- and landscape-sensor technology, as well as in acquisition and delivery of remotely sensed imagery products, will expand the types of real-time monitoring that are possible.

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### LITERATURE CITED

- Bergamo, P., S. Asgari, H. B. Wang, D. Maniezzo, L. Yip, R. E. Hudson, K. Yao, and D. Estrin. 2004. Collaborative sensor networking towards real-time acoustical beamforming in free-space and limited reverberance. *IEEE Transactions on Mobile Computing* 3:211–224.
- Berger, J., S. L. Cain, and K. M. Berger. 2006. Connecting the dots: an invariant migration corridor links the Holocene to the present. *Biology Letters* 2:528–531.
- Ciarniello, L. M., D. C. Heard, D. R. Seip, and M. S. Boyce. 2005. Denning behavior and den site selection of grizzly bears along the Parsnip River, British Columbia, Canada. *Ursus* 16:47–58.
- Clapham, W. M., J. M. Fedders, K. Beeman, and J. P. S. Neel. 2011. Acoustic monitoring system to quantify ingestive behavior of free-grazing cattle. *Computers and Electronics in Agriculture* 76:96–104.
- Cooke, S. J., S. G. Hinch, M. Wikelski, R. D. Andrews, L. J. Kuchel, T. G. Wolcott, and P. J. Butler. 2004. Biotelemetry: a mechanistic approach to ecology. *Trends in Ecology and Evolution* 19:334–343.
- Dettki, H., G. Ericsson, and L. Edenius. 2004. Real-time moose tracking: an internet based mapping application using gps/gsm-collars in Sweden. *Alces* 40:13–21.
- Fryxell, J. M., M. Hazell, L. Borger, B. D. Dalziel, D. T. Haydon, J. M. Morales, T. McIntosh, and R. C. Rosatte. 2008. Multiple movement modes by large herbivores at multiple spatiotemporal scales. *Proceedings of the National Academy of Sciences USA* 105:19114–19119.
- Fryxell, J. M., J. F. Wilmshurst, and A. R. E. Sinclair. 2004. Predictive models of movement by Serengeti grazers. *Ecology* 85:2429–2435.
- Geremia, C., P. J. White, R. L. Wallen, F. G. R. Watson, J. J. Treanor, J. Borkowski, C. S. Potter, and R. L. Crabtree. 2011. Predicting bison migration out of Yellowstone National Park using Bayesian models. *PLoS ONE* 6:e16848.
- Gurarie, E., R. D. Andrews, and K. L. Laidre. 2009. A novel method for identifying behavioural changes in animal movement data. *Ecology Letters* 12:395–408.
- Gwynne, M., and R. H. V. Bell. 1968. Selection of vegetation components by grazing ungulates in the Serengeti National Park. *Nature* 220:390–393.
- Halsey, L. G., J. A. Green, R. P. Wilson, and P. B. Frappell. 2009. Accelerometry to Estimate Energy Expenditure during Activity: Best Practice with Data Loggers. *Physiological and Biochemical Zoology* 82:396–404.
- Hansen, I. J., C. J. Johnson, and H. D. Cluff. 2013a. Synchronicity of movement paths of barren-ground caribou and tundra wolves. *Polar Biology* 36:1363–1371.
- Hansen, M. C., et al. 2013b. High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science* 342:850–853.
- Hebblewhite, M., and D. T. Haydon. 2010. Distinguishing technology from biology: a critical review of the use of GPS telemetry data in ecology. *Philosophical Transactions of the Royal Society B* 365:2303–2312.
- Jonsen, I. D., R. A. Myers, and M. C. James. 2007. Identifying leatherback turtle foraging behaviour from satellite telemetry using a switching state-space model. *Marine Ecology Progress Series* 337:255–264.
- Kertson, B. N., R. D. Spencer, J. M. Marzluff, J. Hepinstall-Cymerman, and C. E. Grue. 2011. Cougar space use and movements in the wildland-urban landscape of western Washington. *Ecological Applications* 21:2866–2881.
- Klinck, H., et al. 2012. Near-real-time acoustic monitoring of beaked whales and other cetaceans using a Seaglider (TM). *PLoS ONE* 7:e36128.



- Knopff, K. H., A. A. Knopff, A. Kortello, and M. S. Boyce. 2010. Cougar kill rate and prey composition in a multiprey system. *Journal of Wildlife Management* 74:1435–1447.
- Knopff, K. H., A. A. Knopff, M. B. Warren, and M. S. Boyce. 2009. Evaluating global positioning system telemetry techniques for estimating cougar predation parameters. *Journal of Wildlife Management* 73:586–597.
- Kunz, T. H., E. B. Arnett, W. P. Erickson, A. R. Hoar, G. D. Johnson, R. P. Larkin, M. D. Strickland, R. W. Thresher, and M. D. Tuttle. 2007. Ecological impacts of wind energy development on bats: questions, research needs, and hypotheses. *Frontiers in Ecology and the Environment* 5:315–324.
- Legendre, P., and L. Legendre. 1998. *Numerical ecology*. Second edition. Elsevier, Amsterdam, The Netherlands.
- Long, R. A., J. G. Kie, R. T. Bowyer, and M. A. Hurley. 2009. Resource selection and movements by female mule deer *Odocoileus hemionus*: effects of reproductive stage. *Wildlife Biology* 15:288–298.
- Lynch, E., L. Angeloni, K. Frstrup, D. Joyce, and G. Wittemyer. 2013. The use of on-animal acoustical recording devices for studying animal behavior. *Ecology and Evolution* 3:2030–7.
- Patterson, T. A., L. Thomas, C. Wilcox, O. Ovaskainen, and J. Matthiopoulos. 2008. State-space models of individual animal movement. *Trends in Ecology and Evolution* 23:87–94.
- Payne, K. B., M. Thompson, and L. Kramer. 2003. Elephant calling patterns as indicators of group size and composition: the basis for an acoustic monitoring system. *African Journal of Ecology* 41:99–107.
- Poole, J. H., and C. J. Moss. 1981. Musth in the African Elephant, *Loxodonta africana*. *Nature* 292:830–831.
- Ropert-Coudert, Y., and R. P. Wilson. 2005. Trends and perspectives in animal-attached remote sensing. *Frontiers in Ecology and the Environment* 3:437–444.
- Singh, N. J., L. Börger, H. Dettki, N. Bunnefeld, and G. Ericsson. 2012. From migration to nomadism: movement variability in a northern ungulate across its latitudinal range. *Ecological Applications* 22:2007–2020.
- Urbano, F., F. Cagnacci, C. Calenge, H. Dettki, A. Cameron, and M. Neteler. 2010. Wildlife tracking data management: a new vision. *Philosophical Transactions of the Royal Society of London B* 365:2177–2185.
- Wall, J., G. Wittemyer, B. Klinkenberg, V. LeMay, and I. Douglas-Hamilton. 2013. Characterizing properties and drivers of long distance movements by elephants (*Loxodonta africana*) in the Gourma, Mali. *Biological Conservation* 157:60–68.
- Ward-Geiger, L. I., G. K. Silber, R. D. Baumstark, and T. L. Pulfer. 2005. Characterization of ship traffic in right whale critical habitat. *Coastal Management* 33:263–278.
- Willis, C. K. R., R. M. R. Barclay, J. G. Boyles, R. M. Brigham, V. Brack, D. L. Waldien, and J. Reichard. 2010. Bats are not birds and other problems with Sovacool's (2009) analysis of animal fatalities due to electricity generation. *Energy Policy* 38:2067–2069.
- Wilson, R. P., E. L. C. Shepard, and N. Liebsch. 2008. Prying into the intimate details of animal lives: use of a daily diary on animals. *Endangered Species Research* 4:123–137.
- Wilson, R. P., C. R. White, F. Quintana, L. G. Halsey, N. Liebsch, G. R. Martin, and P. J. Butler. 2006. Moving towards acceleration for estimates of activity-specific metabolic rate in free-living animals: the case of the cormorant. *Journal of Animal Ecology* 75:1081–1090.
- Wittemyer, G., D. Daballen, and I. Douglas-Hamilton. 2011. Poaching policy: rising ivory prices threaten elephants. *Nature* 476:282–283.

## SUPPLEMENTAL MATERIAL

### Appendix

A description of the real-time monitoring system for elephant tracking, with eight sections detailing each of the system components: (1) collar description and type, (2) temporal sampling regime, (3) deployment locations, (4) data telemetry, (5) data storage, (6) data analysis, (7) alert dissemination, and (8) data access ([Ecological Archives A024-035-A1](#)).