Trends in
Ecology & Evolution

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Biological Earth observation with animal sensors

Walter Jetz, [1,2,3,*]
Grigori Tertitski, [4,*]
Roland Kays, [5,6,7,*] Uschi Mueller, [7]
Martin Wikelski, [7,8,9,*] and
Supporting authors [10]

Space-based tracking technology using low-cost miniature tags is now delivering data on fine-scale animal movement at near-global scale. Linked with remotely sensed environmental data, this offers a biological lens on habitat integrity and connectivity for conservation and human health; a global network of animal sentinels of environmental change.

A novel animal sensor takes off

In September 2020, a tag on the back of a Eurasian blackbird (*Turdus merula*) tagged in Belarus, that had migrated to its wintering grounds in Albania, switched on its transmitter as the International Space Station (ISS) passed 410 km above. The tag sent global positioning system (GPS) location data on the bird´s recent whereabouts as well as onboard sensor data, which the International Cooperation for Animal Research Using Space (ICARUS) receiver aboard the Russian Zvezda Module of the ISS picked up and returned to scientists back on Earth [1] (Figure 1). While only 223 bytes in size, this transmission rang in a new epoch for space-based Earth observations and biological sensing. The new system, based on digital Internet of Things (IoT) technology, will allow the relay of position and behavior from myriad low-cost, miniaturized tracking tags (now 4g, soon 3g, optionally solar powered) at almost global scale and in near-real time.

A connected global system of thousands of mobile 'animal sensors' has the potential to provide a quantum leap for the biological understanding and monitoring of our planet. The environmental associations of animals that drive their movements, finely tuned by evolution, offer an unrivalled biological lens into these habitats themselves. This concept flips the traditional satellite-based Earth observation paradigm: rather than globe-orbiting sensors capturing images of the planet's surface for subsequent interpretation, animals, through countless individual movement decisions, seek out their preferred conditions, sensing the quality and health of ecosystems in real time (Figure 2). Realizing this capability, however, requires engagement from agencies and scientists worldwide to support decentralized coordinated data collection and, to catalyze this engagement, a global demonstration campaign.

Scaling up

The blackbird's data transmission was a long-anticipated milestone (https://www.icarus.mpg.de) [1]. With a new transmission scheme, two-way communication, and mass-produced hardware, ICARUS has not only reduced the size and cost of tracking tags but also increased the number that can be monitored concurrently. Through the ability to simultaneously return data from millions of 'wearables for wildlife', ICARUS complements existing satellite (Argos, Iridium) and ground-based (e.g., GSM, IoT) networks to dramatically expand the number and diversity of animals that can be tracked.

The initial drive for animal tracking has come from animal behavior and migration research. Earlier generations of GPS tags revealed previously unknown migration paths and seasonal gatherings, identified vital corridors and refugia in conservation, and documented important epidemiological links [2,3,10]. Data growth and collaboration have enabled some of the first comparative studies discovering behavioral adjustments to human land use [4] and changes of movements across the Arctic due to climate change [5]. In addition, they have stimulated excitement about the emergence of an entirely new type of animal sentinel-based evidence supporting biodiversity conservation in a rapidly changing world [6,7,11].

Canaries set free

Unlike the caged canary in the coal mine, free-ranging animals pick their own paths and are thus naturally intelligent sensors, fine-tuned by evolution. They actively seek out, or avoid, a set of environmental conditions and show distinct reactions to unusual weather, storms, and some natural disasters [8]. When linked to concurrently remotely sensed data from satellites, and through sensors' onboard tags, their movement tracks record individually encountered environmental conditions. This enables an unprecedented quantification of the habitat use, environmental niches and ecological boundaries of animals and, with baseline data in place, real-time monitoring of change. Thereby, tracked animals can add essential biological meaning to the vast, ongoing remote-sensing data collection and act as canaries in the coal mine set free: signalers and sentinels of environmental conditions through their selection, avoidance, or death.

The satellite–animal interlink could extend to active digital handholding: satellites could be tasked with following particular individuals for extra information or, in real time, tune into those showing abnormal behavior or sudden avoidance of places expected to be suitable. Agencies or conservation groups could receive alerts if typically used habitats or conservation areas are suddenly avoided or cause death (e.g., due to illegal encroachment or hunting). Such a system would substantially enhance ecological-change detection from remotely sensed signals, complementing existing data and approaches, for example, for remotely sensed deforestation alerts or spatially

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Figure 1. Animals on biological Earth observation mission, as captured from 11 March 2021 to 3 November 2021 by the International Cooperation for Animal Research Using Space (ICARUS) tracking system onboard the International Space Station. Most species are global positioning system (GPS) tracked for the first time in near-real time during their migratory cycles. The global map displays large-scale tracks of selected individuals of 15 species; the inset maps show regional-scale tracks of five species during this period. (A) Mountain plover (*Charadrius montanus*); (B) Arctic tern (*Sterna paradisaea*); (C) turtle dove (*Streptopelia turtur*); (D) common cuckoo (*Cuculus canorus*); (E) straw-colored fruit bat (*Eidolon helvum*); (F) saiga (*Saiga tatarica*); (G) European blackbird (*Turdus merula*); (H) Swinhoe's snipe (*Gallinago megala*); (I) Eastern marsh harrier (*Circus spilonotus*); (J) oriental cuckoo (*Cuculus optatus*); (K) red-footed falcon (*Falco vespertinus*); (L) sooty tern (*Onychoprion fuscatus*); (populations in the Atlantic, the Indian Ocean, and Polynesia); (M) Hudsonian godwit (*Limosa haemastica*); (N) bristle-thighed curlew (*Numenius tahitiensis*); (O) wandering tattler (*Tringa incana*). Note that, for example, Hudsonian godwits fly nonstop from nonbreeding locations in Southern Chile to Mexico or across Central America to land in Texas, USA; oriental cuckoos fly over the ocean from Japan to Papua New Guinea; and common cuckoos cross the Indian Ocean from India to Africa. Arctic terns migrate from the White Sea in Russia to Spitzbergen, Greenland, and Iceland to Western Africa. Blackbirds move into Mediterranean areas from Russia, Poland, and Germany. Polynesian migrants link Hawaii and Alaska. Explore examples of individual ranges, niches, and movement paths emerging from these new data at https://animallives.org.

fixed conservation technology, such as camera traps.

100 000 Sentinels

Imagine a representative set of 100 000 animals from 500 species equipped with space-based GPS tracking tags that deliver half-hourly data. At a 3g tag size, such a system is able to address around 40% of birds and over 50% of mammals (i.e., a total of ca 7000 potential species) and hundreds of species of crocodiles, turtles, and large lizards (for a 5% weight limit). This expanded hyper-speciose taxonomic (and geographic) scope opens an entirely new phase of animal-based Earth observation. Deploying this many tags is certainly a challenge, but remember, the ISS-tracked blackbird was preceded by tens of thousands of blackbirds equipped with leg bands instead. Thanks to a vast international network of volunteers, ca 3.5 million individual birds have been captured and marked every year since 1960, globally [9] (with <1% ever resighted or recovered to provide a second data point), and probably hundreds of thousands

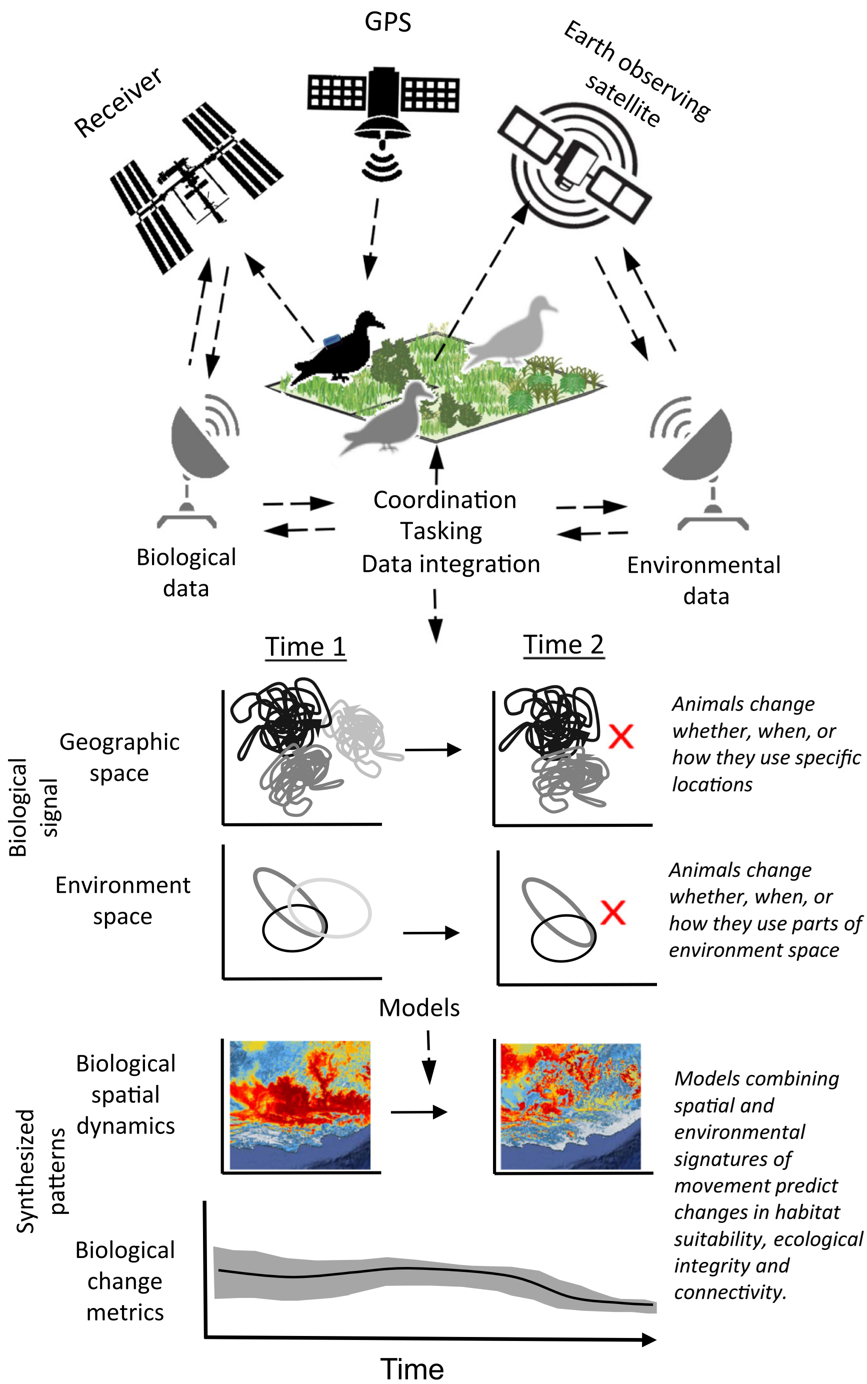

Figure 2. Animal tracking-based Earth observation. Global positioning system (GPS) tracks of animal movements received via the space link are matched with remotely sensed environmental data. This enables the monitoring of animal use of geographic and environment space over time (illustrated for three example biological units; e.g., individuals, populations, species). Combination with contiguous remote sensing layers and models enables mapping and temporal tracking of biological dynamics captured directly and indirectly by the tracked animals.

of mammals. While not all species will be straightforward or justifiable targets for GPS tags, the potential set is large enough to enable ecologically representative and global coverage. Past experience and initial ICARUS interest suggest that wildlife agencies, non-governmental organizations, scientists, and bird banders would carry the large majority of deployments, with coordination and targeted campaigns needed to ensure coverage. The International Bio-Logging Society (https://www.bio-logging.net) could play a role in supporting such a global coordination. With a receiver in place, tag hardware cost at scale decreasing to US$100 or less each, and a yearly redeployment of 50 000 new tags, this results in a US$10–15 million annual cost, tremendous value added to environmental satellite missions at a small fraction of their typical cost.

We expect that, combined with other data on traits and behaviors, space–time–environment information from thousands of species will enable a more functional interpretation of the ecosystem consequences of biodiversity. Across scales of organismal organization, but also across space and time, these measurements will allow pinning down of the plasticity and adaptive potential around realized change in animal niches and space use. The detailed capture of individual lifetime tracks, when linked with environmental and individual phenotypic and genomic data, provides an unprecedented tool for evolutionary study and offers new life-history, geospatial, and environmental niche dimensions for specimens archived or exhibited in museums. For potential animal reservoirs of infectious diseases, Earth observation with animal sensors can help to identify potential hotspots of disease transmission and map and monitor the potential for long-distance and cross-border transmissions [10]. Tracking of individuals with antibodies offers epidemiologists the potential to pinpoint the location of the true hosts of zoonotics such as Ebola and coronavirus disease 2019 (COVID-19).

With so many animals tracked, many intriguing stories will emerge about individual animals that will have the potential to capture the imagination of people worldwide. The tracked animals provide the daily drama that can be part of digitally-rich media campaigns around tagged individuals that support education and discovery, and can engage citizen scientists to collect ancillary observations, enriching the data record even further. The potential to adopt and follow single individuals and their fates can connect people to biodiversity issues, both at their doorstep and far away, and support educational uses and conservation funding.

Concluding remarks: engaging scientists and agencies, a call to action

Realizing these opportunities will require the engagement of and contributions from government agencies, the science community, and beyond. At agency level, a shift in traditional perceptions and approaches to Earth observation and monitoring will be required, together with interagency collaboration among and within nations. The ICARUS ground-to-space IoT is designed to be an open system for any organization to join and augment the global readout capacity or leverage for an improved system. The success of the presented vision will also rely on global collaboration and coordination of biodiversity monitoring among sovereign territories. With the GEO Biodiversity Observation Network (https://geobon.org) and its associated research community, international platforms and scientific principles for globally coordinated and integrated biodiversity monitoring are in place. Through model-based integration with other biodiversity data in platforms such as Map of Life (https://mol.org), the envisioned animal-based Earth observation can inform Essential Biodiversity Variables and indicators for the tracking of progress toward international goals on maintaining ecological integrity and connectivity or provide management-relevant short-term forecasting [7].

As tag deployments will rely on individual scientist's participation, a willingness to follow agreed data standards and share data is vital. Effective Earth observation via animals will thus require development and openness around new data-sharing and -use models, including the near-immediate sharing of limited anonymized information that near-real time monitoring and model-based short-term forecasting depend on. Community engagement is needed to develop effective approaches for the citation of tracking data to support appropriate attribution and recognition. As one scales this vision to a truly global endeavor, challenges certainly remain, including sufficient capacity to support best scientific practice, benefit sharing, and the engagement of regional and local stakeholders.

With the ICARUS system now online, a globally coordinated '100 000 animal sentinels' campaign is possible and would establish an unrivalled bioenvironmental baseline record. With the larger community engaged, it would be the start of ongoing real-time sensing of living conditions on Earth by animals themselves. Akin to hyperspectral remote sensing systems [12], it would realize hyper-speciose, and thus multifaceted, *in situ* biological Earth observation.

Declaration of interests

No interests are declared.

[1] Center for Biodiversity and Global Change, Yale University, New Haven, CT 06520, USA
[2] Max Planck Yale Center for Biodiversity Movement and Global Change, Yale University, New Haven, CT 06520, USA
[3] Department of Ecology and Evolutionary Biology, Yale University, New Haven, CT 06520, USA
[4] Institute of Geography, Russian Academy of Sciences, 119017 Moscow, Russia
[5] North Carolina Museum of Natural Sciences, Raleigh, NC, USA
[6] Department of Forestry and Environmental Resources, North Carolina State University, Raleigh, NC, USA
[7] Department of Migration, Max Planck Institute of Animal Behavior, 78315 Radolfzell, Germany
[8] Max Planck Yale Center for Biodiversity Movement and Global Change, Max Planck Institute of Animal Behavior, 78315 Radolfzell, Germany
[9] Centre for the Advanced Study of Collective Behaviour, University of Konstanz, 78457 Konstanz, Germany
[10]Supporting authors: Susanne Åkesson, Yury Anisimov, Aleksey Antonov, Walter Arnold, Franz Bairlein, Oriol Baltà, Diane Baum, Mario Beck, Olga Belonovich, Mikhail Belyaev, Matthias Berger, Peter Berthold, Steffen Bittner, Stephen Blake, Barbara Block, Daniel Bloche, Katrin Boehning-Gaese, Gil Bohrer, Julia Bojarinova, Gerhard Bommas, Oleg Bourski, Albert Bragin, Alexandr Bragin, Rachel Bristol, Vojtěch Brlík, Victor Bulyuk, Francesca Cagnacci, Ben Carlson, Taylor K. Chapple, Kalkidan F. Chefira, Yachang Cheng, Nikita Chernetsov, Grzegorz Cierlik, Simon S. Christiansen, Oriol Clarabuch, William Cochran, Jamie Margaret Cornelius, Iain Couzin, Margret C. Crofoot, Sebastian Cruz, Alexander Davydov, Sarah Davidson, Stefan Dech, Dina Dechmann, Ekaterina Demidova, Jan Dettmann, Sven Dittmar, Dmitry Dorofeev, Detlev Drenckhahn, Vladimir Dubyanskiy, Nikolay Egorov, Sophie Ehnbom, Diego Ellis-Soto, Ralf Ewald, Chris Feare, Igor Fefelov, Péter Fehérvári, Wolfgang Fiedler, Andrea Flack, Magnus Froböse, Ivan Fufachev, Pavel Futoran, Vyachaslav Gabyshev, Anna Gagliardo, Stefan Garthe, Sergey Gashkov, Luke Gibson, Wolfgang Goymann, Gerd Gruppe, Chris Guglielmo, Phil Hartl, Anders Hedenström, Arne Hegemann, Georg Heine, Mäggi Hieber Ruiz, Heribert Hofer, Felix Huber, Fabiola Iannarilli, Marc Illa, Arkadiy Isaev, Bent Jakobsen, Lukas Jenni, Susi Jenni-Eiermann, Brett Jesmer, Frédéric Jiguet, Tatiana Karimova, N. Jeremy Kasdin, Fedor Kazansky, Ruslan Kirillin, Thomas Klinner, Andreas Knopp, Andrea Kölzsch, Alexander Kondratyev, Marco Krondorf, Pavel Ktitorov, Olga Kulikova, R. Suresh Kumar, Claudia Künzer, Anatoliy Larionov, Christine Larose, Felix Liechti, Nils Linek, Ashley Lohr, Anna Lushchekina, Kate Mansfield, Maria Matantseva, Mikhail Markovets, Peter Marra, Juan F. Masello, Jörg Melzheimer, Myles H.M. Menz, Stephen Menzie, Swetlana Meshcheryagina, Dale Miquelle, Vladimir Morozov, Andrey Mukhin, Inge Müller, Thomas Mueller, Juan G. Navedo, Ran Nathan, Luke Nelson, Zoltán Németh, Scott Newman, Ryan Norris, Innokentiy Okhlopkov, Wioleta Oleś, Ruth Oliver, Teague O'Mara, Peter Palatitz, Jesko Partecke, Ryan Pavlick, Anastasia Pedenko, Julie Pham, Daniel Piechowski, Allison Pierce, Theunis Piersma, Wolfgang Pitz, Dirk Plettemeier, Irina Pokrovskaya, Liya Pokrovskaya, Ivan Pokrovsky, Morrison Pot, Petr Procházka, Petra Quillfeldt, Eldar Rakhimberdiev, Marilyn Ramenofsky, Ajay Ranipeta, Jan Rapczyński, Magdalena Remisiewicz, Viatcheslav Rozhnov, Froukje Rienks, Vyacheslav Rozhnov, Christian Rutz, Vital Sakhvon, Nir Sapir, Kamran Safi, Friedrich Schäuffelhut, David Schimel, Andreas Schmidt, Judy Shamoun-Baranes, Alexander Sharikov, Laura Shearer, Evgeny Shemyakin, Sherub, Ryan Shipley, Yanina Sica, Thomas B. Smith, Sergey Simonov, Katherine Snell, Aleksandr Sokolov, Vasiliy Sokolov, Olga Solomina, Fernando Spina, Kamiel Spoelstra, Martin Storhas, Tatiana Sviridova, George Swenson, Jr, Phil Taylor, Kasper Thorup, Arseny Tsvey, Marlee Tucker, Woody Turner, Henk van der Jeugd, Louis van Schalkwyk, Mariëlle van Toor, Pauli Viljoen, Marcel E. Visser, Tamara Volkmer, Andrei Volkov, Sergey Volkov, Oleg Volkow, Jan A.C. von Rönn, Bernd Vorneweg, Bettina Wachter, Jonas Waldenström, Martin Wegmann, Aloysius Wehr, Rolf Weinzierl, Johannes Weppler, David Wilcove, Timm Wild, Hannah J. Williams, John Wilshire, John Wingfield, Michael Wunder, Anna Yachmennikova, Scott Yanco, Elisabeth Yohannes, Amelie Zeller, Christian Ziegler, Anna Zięcik, and Cheryl Zook. Affiliations: Susanne Åkesson, Department of Biology, Center for Animal Movement Research, Lund University, Lund, Sweden; Yuri Anisimov, Baikalskiy Nature Reserve, Tanhoi, Russia; Aleksey Antonov, Khingan State Nature Reserve, Arkhara, Russia; Walter Arnold, Research Institute of Wildlife Ecology, University of Veterinary Medicine, Vienna, Austria;

Franz Bairlein, Max Planck Institute of Animal Behavior, Radolfzell, Germany; Oriol Baltà, Catalan Ornithological Institute, Nat-Museu de Ciències Naturals de Barcelona, Barcelona, Spain; Diane Baum, Conservation and Fisheries, Ascension Island Government, Ascension Island; Mario Beck, Rohde & Schwarz INRADIOS GmbH, Dresden, Germany; Olga Belonovich, Commander Islands Nature and Biosphere Reserve, Nikolskoye, Russia; Mikhail Belyaev, S.P. Korolev RSC Energia, Korolev, Russia; Matthias Berger, Schäuffelhut Berger GmbH, Unterhaching, Germany; Peter Berthold, Max Planck Institute of Animal Behavior, Radolfzell, Germany; Steffen Bittner, Rohde & Schwarz INRADIOS GmbH, Dresden, Germany; Stephen Blake, Department of Biology, St. Louis University, St. Louis, MO, USA and WildCare Institute, Saint Louis Zoo, 1 Government Drive, Saint Louis, MO 63110 USA; Barbara Block, Stanford WOODS Institute for the Environment, Stanford, CA, USA; Daniel Bloche, Blåvand Birdobservatory, Blåvand, Denmark; Katrin Boehning-Gaese, Senckenberg Biodiversity and Climate Research Centre (SBiK-F), Frankfurt (Main), Germany and Goethe University Frankfurt am Main, Institute for Ecology, Evolution and Diversity, Frankfurt (Main), Germany; Gil Bohrer, Department of Civil, Environmental and Geodetic Engineering, The Ohio State University, Columbus, OH, USA; Julia Bojarinova, Department of Vertebrate Zoology, Faculty of Biology, St. Petersburg State University, St. Petersburg, Russia; Gerhard Bommas, SatCom Consulting, Immenstaad, Germany; Albert Bragin, FGBU National Park Kenozersky, Arkhangelsk, Russia; Alexandr Bragin, Rostov State Biosphere Reserve, Rostov-on-Don, Russia; Rachel Bristol, La Batie, Beau Vallon, Mahe, Seychelles; Vojtěch Brlík, Department of Ecology, Charles University, Prague, Czech Republic; Oleg Bourski, A.N. Severtsov Institute of Ecology and Evolution, RAS, Moscow, Russia; Victor Bulyuk, Zoological Institute, RAS, St. Petersburg, Russia, Francesca Cagnacci, Department of Biodiversity and Molecular Ecology, Research and Innovation Centre, Fondazione Edmund Mach, San Michele all'Adige, Italy; Ben Carlson, Max Planck Yale Center for Biodiversity Movement and Global Change, Yale University, New Haven, CT, USA; Taylor K. Chapple, Coastal Oregon Marine Experiment Station, Oregon State University, Newport, OR, USA; Yachang Cheng, Department of Ecology, Sun Yat-sen University, Shenzhen, China, and Department of Migration, Max Planck Institute of Animal Behavior, Radolfzell, Germany, and Department of Biology, University of Konstanz, Konstanz, Germany; Kalkidan F. Chefira, Max Planck Yale Center for Biodiversity Movement and Global Change, Yale University, New Haven, CT, USA; Nikita Chernetsov, Zoological Institute, Russian Academy of Sciences, St. Petersburg, Russia; Grzegorz Cierlik, Akcja Carpatica, Rzeszów, Poland; Simon S. Christiansen, Skagen Bird Observatory, BirdLife Denmark, Skagen, Denmark; Oriol Clarabuch, Catalan Ornithological Institute, Nat-Museu de Ciències Naturals de Barcelona, Barcelona, Spain; William Cochran, University of Illinois, Urbana-Champaign, IL, USA; Jamie Margaret Cornelius, Department of Integrative Biology, Oregon State University, Corvallis, OR, USA; Iain Couzin, Centre for the Advanced Study of Collective Behaviour, University of Konstanz, Konstanz, Germany and Department of Collective Behavior, Max Planck Institute of Animal Behavior, Konstanz, Germany; Margret C. Crofoot, Department of the Ecology of Animal Societies, Max Planck Institute of Animal Behavior, Konstanz, Germany; Sebastian Cruz, independent researcher; Alexander Davydov, Biological Station Rybachy of Zoological Institute of Russian Academy of Sciences, St. Petersburg, Russia; Sarah Davidson, Department of Migration, Max Planck Institute of Animal Behavior, Radolfzell, Germany, Centre for the Advanced Study of Collective Behaviour, University of Konstanz, Konstanz, Germany and Department of Civil, Environmental and Geodetic Engineering, The Ohio State University, Columbus, OH, USA; Stefan Dech, German Aerospace Center (DLR), German Remote Sensing Data Center (DFD), Oberpfaffenhofen, Germany; Dina Dechmann, Department of Migration, Max Planck Institute of Animal Behavior, Radolfzell, Germany; Ekaterina Demidova, A.N. Severtsov Institute of Ecology and Evolution, RAS, Moscow, Russia; Jan Dettmann Telecommunications and Integrated Applications, European Space Agency, Harwell Oxford, UK; Sven Dittmar, SpaceTech GmbH, Immenstaad, Germany; Dmitry Dorofeev, All-Russian Research Institute for Environmental Protection, Moscow, Russia; Detlev Drenckhahn, former spokesperson of the Leopoldina Commission for Environmental Sciences, Halle, Germany and former president of the Word Wide Fund for Nature, Berlin, Germany; Vladimir Dubyanskiy, Stavropol Plague Control Institute, Stavropol, Russia; Nikolay Egorov, Institute for Biological Problems of Cryolithozone, RAS, Yakutsk, Russia; Sophie Ehnbom, Falsterbo Fågelstation/Falsterbo Bird Observatory, Falsterbo, Sweden; Diego Ellis-Soto, Max Planck Yale Center for Biodiversity Movement and Global Change, Yale University, New Haven, CT, USA; Ralf Ewald, German Space Agency, Civil Security and Regulatory Affairs, German Aerospace Center (DLR), Bonn, Germany; Chris Feare, WildWings Bird Management, Haslemere, Surrey, UK; Igor Fefelov, Irkutsk State University, Irkutsk, Russia; Péter Fehérvári, Department of Biomathematics and Informatics, University of Veterinary Medicine, Budapest, Hungary; Wolfgang Fiedler, Department of Migration, Max Planck Institute of Animal Behavior, Radolfzell, Germany; Andrea Flack, Department of Migration, Max Planck Institute of Animal Behavior, Radolfzell, Germany; Magnus Froböse, Context Film, Munich, Germany; Ivan Fufachev, Arctic Research Station of Institute of Plant and Animal Ecology, UB RAS, Labytnangi, Russia; Pavel Futoran, FGBU National Park Kenozersky, Arkhangelsk, Russia; Vyachaslav Gabyshev, Institute for Biological Problems of Cryolithozone, RAS, Yakutsk, Russia; Anna Gagliardo, Department of Biology, University of Pisa, Pisa, Italy; Stefan Garthe, ECOLAB - Group Animal Ecology, Conservation & Science Communication, Christian-Albrechts-Universität zu Kiel, Germany; Sergey Gashkov, National Research Tomsk State University, Tomsk, Russia; Luke Gibson, School of Environmental Science and Engineering, Southern University of Science and Technology, Shenzhen, China; Wolfgang Goymann, Department for Behavioural Neurobiology, Max Planck Institute for Ornithology, Seewiesen, Germany; Gerd Gruppe, Space Administration, German Aerospace Center (DLR), Bonn, Germany; Chris Guglielmo, Department of Biology, Advanced Facility for Avian Research, University of Western Ontario, London, ON, Canada; Phil Hartl, Munich, Germany; Anders Hedenström, Department of Biology, Lund University, Lund, Sweden; Arne Hegemann, Department of Biology, Lund University, Lund, Sweden; Georg Heine, University of Konstanz, Konstanz, Germany; Mäggi Hieber Ruiz, Department of Migration, Max Planck Institute of Animal Behavior, Radolfzell, Germany; Heribert Hofer, Leibniz Institute for Zoo and Wildlife Research, Berlin, Germany and Department of Veterinary Medicine, Berlin, Germany; Felix Huber, Steinbeis-Transferzentrum Raumfahrt, Gäufelden, Germany and GSOC – Deutsches Zentrum für Luft- und Raumfahrt (DLR), Oberpfaffenhofen, Germany; Fabiola Iannarilli, Max Planck Yale Center for Biodiversity Movement, Yale University, New Haven, CT, USA; Marc Illa, Catalan Ornithological Institute, Nat-Museu de Ciències Naturals de Barcelona, Barcelona, Spain; Arkadiy Isaev, Institute for Biological Problems of Cryolithozone, RAS, Yakutsk, Russia; Bent Jakobsen, Blåvand Birdobservatory, Blåvand, Denmark; Lukas Jenni, Swiss Ornithological Institute, Sempach, Switzerland; Susi Jenni-Eiermann, Swiss Ornithological Institute, Sempach, Switzerland; Brett Jesmer, Max Planck Yale Center for Biodiversity Movement and Gobal Change, Yale University, New Haven, CT, USA and Department of Fish and Wildlife Conservation, Virginia Tech, Blacksburg, VA 2406, USA; Frédéric Jiguet, FJ, UMR7204 CESCO, MNHN-CNRS-Sorbonne Université, Paris, France; Tatiana Karimova, A.N. Severtsov Institute of Ecology and Evolution, RAS, Moscow, Russia; N. Jeremy Kasdin, Professor of Mechanical and Aerospace Engineering, Emeritus, Princeton University, Princeton, NJ, USA; Fedor Kazansky, Kronotsky State Biosphere Reserve, Russia; Ruslan Kirillin, Institute for Biological Problems of Cryolithozone, RAS, Yakutsk, Russia; Thomas Klinner, Verein Jordsand, Inselhof, Greifswalder Oie, Germany; Andreas Knopp, Institute of Information Technology, Universität der Bundeswehr, Munich, Germany; Andrea Kölzsch, Department of Migration, Max Planck Institute of Animal Behavior, Radolfzell, Germany; Alexander Kondratyev, Institute of Biological Problems of the North, FEB RAS, Magadan, Russia; Marco Krondorf, Chair of Communication Technology, HTWK Leipzig, Germany; Pavel Ktitorov, Institute of Biological Problems of the North, FEB RAS, Russia; Olga Kulikova, Institute of Biological Problems of the North, FEB RAS, Russia; R. Suresh Kumar, Department of Endangered Species Management, Wildlife Institute of India, Chandrabani, Dehradun, Uttarakhand, India; Claudia Künzer, German Remote Sensing Data Center (DFD), German Aerospace Center (DLR), Wessling, Germany and Institute of Geography and Geology, University of Wuerzburg, Wuerzburg, Germany; Anatoliy Larionov, Institute for Biological Problems of Cryolithozone, RAS, Yakutsk, Russia; Christine Larose, WildWings Bird Management, Pointe au Sel, Au Cap, Mahe, Seychelles; Felix Liechti, Swiss Ornithological Institute, Sempach, Switzerland; Nils Linek, Max Planck Institute of Animal Behavior, Radolfzell, Germany and Department of Biology, University of Konstanz, Konstanz, Germany; Ashley Lohr, North Carolina Museum of Natural Sciences, Raleigh, NC, USA; Anna Lushchekina, A.N. Severtsov Institute of Ecology and Evolution, RAS, Moscow, Russia; Kate Mansfield, Department of Biology, University of Central Florida, Orlando, FL, USA; Maria Matantseva, Institute of Biology, Karelian Research Center, RAS, Petrozavodsk, Russia; Mikhail Markovets, Zoological Institute, RAS, St. Petersburg, Russia; Peter Marra, Department of Biology, McCourt School of Public Policy, Georgetown University, Washington, DC, USA; Juan F. Masello, Department of Animal Ecology and Systematics, Justus Liebig University Giessen, Giessen, Germany; Jörg Melzheimer, Department of Evolutionary Ecology, Leibniz Institute for Zoo and Wildlife Research, Berlin, Germany; Myles H.M. Menz, Max Planck Institute of Animal Behavior, Radolfzell, Germany; Stephen Menzie, Falsterbo Fågelstation/Falsterbo Bird Observatory, Falsterbo, Sweden; Swetlana Meshcheryagina, Institute of Plant and Animal Ecology, UB RAS, Ekaterinburg, Russia; Dale Miquelle, Wildlife Conservation Society, New York, NY, USA; Vladimir Morozov, All-Russian Research Institute for Environmental Protection, Moscow, Russia; Andrey Mukhin, Biological Station Rybachy of Zoological Institute of Russian Academy of Sciences, St. Petersburg, Russia; Inge Müller, Max Planck Institute of Animal Behavior, Radolfzell, Germany; Thomas Mueller, Senckenberg Biodiversity and Climate Research Centre (SBiK-F), Frankfurt (Main), Germany and Department of Biological Sciences, Goethe University Frankfurt, Frankfurt (Main), Germany; Juan G. Navedo, Bird Ecology Lab, Instituto de Ciencias Marinas y Limnológicas, Universidad Austral de Chile, Valdivia, Chile; Ran Nathan, Alexander Silberman Institute of Life Sciences, Hebrew University of Jerusalem, Jerusalem, Israel; Luke Nelson, Blåvand Birdobservatory, Blåvand, Denmark; Zoltán Németh, MTA-DE Behavioural Ecology Research Group, Department of Evolutionary Zoology and Human Biology, University of Debrecen, Debrecen, Hungary; Scott Newman, Food and Agriculture Organization of the United Nations (FAO), Regional Office for Asia and the Pacific, Bangkok, Thailand; Ryan Norris, Department of Integrative Biology, University of Guelph, Guelph, ON, Canada; Innokentiy Okhlopkov, Institute for Biological Problems of Cryolithozone, RAS, Yakutsk, Russia; Wioleta Oleś, Akcja Carpatica, Rzeszów, Poland; Ruth Oliver, Max Planck Yale Center for Biodiversity Movement, Yale University, New Haven, CT, USA; Teague O'Mara, Max Planck Institute of Animal Behavior, Radolfzell, Germany, Department of Biological Sciences, Southeastern Louisiana University, Hammond, LA, USA and Smithsonian Tropical Research Institute, Panama City, Panama; Peter Palatitz, MME/BirdLife Hungary, Budapest, Hungary; Jesko Partecke, Department of Migration, Max Planck Institute of Animal Behavior, Radolfzell, Germany; Ryan Pavlick, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA; Anastasia Pedenko, Moscow State Pedagogical University, Moscow, Russia; Julie Pham, Max Planck Yale Center for Biodiversity Movement and Global Change, Yale University, New Haven, CT, USA; Daniel Piechowski, Max Planck Institute of Animal Behavior, Radolfzell, Germany; Allison Pierce, Department of Integrative Biology, University of Colorado, Denver, CO, USA; Theunis Piersma, Conservation Ecology Group, Groningen, Institute for Evolutionary Life Sciences (GELIFES), University of Groningen, Groningen, The Netherlands; Wolfgang Pitz, SpaceTech GmbH, Immenstaad, Germany; Dirk Plettemeier, Institute of Communication Technology, Technische Universität Dresden, Dresden, Germany; Irina Pokrovskaya, Institute of Geography RAS, Moscow, Russia; Liya Pokrovskaya, Moscow State University, Moscow, Russia; Ivan Pokrovsky, Department of

Migration, Max Planck Institute of Animal Behavior, Radolfzell, Germany; Morrison Pot, Department of Animal Ecology, Netherlands Institute of Ecology (NIOO-KNAW), Wageningen, The Netherlands and Vogeltrekstation – Dutch Centre for Avian Migration and Demography, Netherlands Institute of Ecology (NIOO-KNAW), Wageningen, The Netherlands; Petr Procházka, Institute of Vertebrate Biology, Czech Academy of Sciences, Brno, Czech Republic; Petra Quillfeldt, Department of Animal Ecology and Systematics, Justus Liebig University Giessen, Giessen, Germany; Eldar Rakhimberdiev, Department of Theoretical and Computational Ecology, Institute for Biodiversity and Ecosystem Dynamics, University of Amsterdam, Amsterdam, The Netherlands and Department of Vertebrate Zoology, Lomonosov Moscow State University, Moscow, Russia; Marilyn Ramenofsky, Avian Migration Laboratory, Department of NPB, University of California, Davis, CA, USA; Ajay Ranipeta, Max Planck Yale Center for Biodiversity Movement, Yale University, New Haven, CT, USA; Jan Rapczyński, Akcja Carpatica, Rzeszów Poland; Magdalena Remisiewicz, Bird Migration Research Station, Faculty of Biology, University of Gdańsk, Gdańsk, Poland; Viatcheslav Rozhnov, A.N. Severtsov Institute of Ecology and Evolution of Russian Academy of Sciences, Moscow, Russia; Froukje Rienks, Netherlands Institute of Ecology (NIOO-KNAW), Wageningen, The Netherlands; Vyacheslav Rozhnov, A.N. Severtsov Institute of Ecology and Evolution, RAS, Moscow, Russia; Christian Rutz, Centre for Biological Diversity, School of Biology, University of St Andrews, St Andrews, UK; Vital Sakhvon, Department of Zoology, Faculty of Biology, Belarusian State University, Minsk, Belarus; Nir Sapir, Department of Evolutionary and Environmental Biology and Institute of Evolution, University of Haifa, Haifa, Israel; Friedrich Schäuffelhut, Schäuffelhut Berger GmbH, Unterhaching, Germany; Kamran Safi, Max Planck Institute of Animal Behavior, Radolfzell, Germany; David Schimel, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA; Andreas Schmidt, Max Planck Institute of Animal Behavior, Radolfzell, Germany; Judy Shamoun-Baranes, Department of Theoretical and Computational Ecology, Institute for Biodiversity and Ecosystem Dynamics, University of Amsterdam, Amsterdam, The Netherlands; Alexander Sharikov, Moscow State Pedagogical University, Moscow, Russia; Laura Shearer, Ascension Island Government Conservation and Fisheries Department, Georgetown, Ascension Island; Evgeny Shemyakin, Institute for Biological Problems of Cryolithozone, RAS, Yakutsk, Russia; Sherub Sherub, Max Planck Institute of Animal Behavior, Radolfzell, Germany and Ugyen Wangchuck Institute for Conservation and Environment Research, Bhutan; Ryan Shipley, Max Planck Institute of Animal Behavior, Radolfzell, Germany; Yanina Sica, Max Planck Yale Center for Biodiversity Movement, Yale University, New Haven, CT, USA; Thomas B. Smith, Center for Tropical Research and Institute of the Environment and Sustainability, University of California, Los Angeles, CA, USA; Sergey Simonov, Institute of Biology, Karelian Research Center, RAS, Petrozavodsk, Russia, Katherine Snell, Department of Migration, Max Planck Institute of Animal Behavior, Radolfzell, Germany; Aleksandr Sokolov, Arctic Research Station of Institute of Plant and Animal Ecology, UB RAS, Labytnangi, Russia; Vasiliy Sokolov, Institute of Plant and Animal Ecology, UB RAS, Ekaterinburg, Russia; Olga Solomina, Institute of Geography, Russian Academy of Sciences, Moscow, Russia and National Research University Higher School of Economics, Moscow, Russia; Mikhail Soloviev, Moscow State University, Russia; Fernando Spina, ISPRA Istituto Superiore per la Protezione e la Ricerca Ambientale, Roma, Italy; Kamiel Spoelstra, Department of Animal Ecology, Netherlands Institute of Ecology (NIOO-KNAW), Wageningen, The Netherlands; Martin Storhas, Schäuffelhut Berger GmbH, Unterhaching, Germany; Tatiana Sviridova, A.N. Severtsov Institute of Ecology and Evolution, RAS, Moscow, Russia; George Swenson, Jr, Department of Laboratory Wave Propagation, University of Illinois, Urbana-Champaign, IL, USA; Phil Taylor, Acadia University, Wolfville, NS, Canada; Kasper Thorup, Center for Macroecology, Evolution and Climate, Globe Institute, University of Copenhagen, Copenhagen, Denmark; Arseny Tsvey, Biological Station Rybachy of Zoological Institute of Russian Academy of Sciences, St. Petersburg, Russia; Marlee Tucker, Department of Environmental Science, Radboud Institute for Biological and Environmental Sciences, Radboud University, Nijmegen, The Netherlands; Woody Turner, NASA Headquarters Earth Science Division, Washington, DC, USA; Henk van der Jeugd, Vogeltrekstation – Dutch Centre for Avian Migration and Demography NIOO-KNAW, Wageningen, The Netherlands; Louis van Schalkwyk, Department of Agriculture, Land Reform and Rural Development, Government of South Africa, Department of Migration, Max Planck Institute of Animal Behavior, Radolfzell, Germany and Department of Veterinary Tropical Diseases, Faculty of Veterinary Science, University of Pretoria, Pretoria, South Africa; Mariëlle van Toor, Centre for Ecology and Evolution in Microbial model Systems (EEMiS), Linnaeus University, Kalmar, Sweden; Pauli Viljoen, Scientific Services, Kruger National Park, Skukuza, South Africa; Marcel E. Visser, Netherlands Institute of Ecology (NIOO-KNAW), Wageningen, The Netherlands and GELIFES – Groningen Institute for Evolutionary Life Sciences, Groningen University, The Netherlands; Tamara Volkmer, Max Planck Institute of Animal Behavior, Radolfzell, Germany and Department of Biology, University of Konstanz, Konstanz, Germany; Andrey Volkov, FGBU National Park Kenozersky, Nizhniy Novgorod, Russia; Sergey Volkov, A.N. Severtsov Institute of Ecology and Evolution, RAS, Moscow, Russia; Oleg Volkov, S.P. Korolev RSC Energia, Korolev, Russia; Jan A.C. von Rönn, Swiss Ornithological Institute, Sempach, Switzerland and Verein Jordsand, Inselhof, Greifswalder Oie, Germany; Bernd Vorneweg, Max Planck Institute of Animal Behavior, Radolfzell, Germany; Bettina Wachter, Department of Evolutionary Ecology, Leibniz Institute for Zoo and Wildlife Research (IZW), Berlin, Germany; Jonas Waldenström, Centre for Ecology and Evolution in Microbial Model Systems (EEMiS), Linnaeus University, Kalmar, Sweden; Martin Wegmann, Department of Remote Sensing, Institute of Geography, University of Würzburg, Würzburg, Germany; Aloysius Wehr, Institute of Navigation, University of Stuttgart, Stuttgart, Germany; Rolf Weinzierl, Seehausen, Germany; Johannes Weppler, German Space Agency, Human Spaceflight, ISS and Exploration, German Aerospace Center (DLR), Bonn, Germany; David Wilcove, Department of Ecology and Evolutionary Biology, Princeton University, Guyot Hall, Princeton, NJ, USA; Timm Wild, Max Planck Institute of Animal Behavior, Radolfzell, Germany; Hannah J. Williams, Department of Migration, Max Planck Institute of Animal Behavior, Radolfzell, Germany; John H. Wilshire, Max Planck Yale Center for Biodiversity Movement, Yale University, New Haven, CT, USA; John Wingfield, University of California, Davis, CA 95616, USA; Michael Wunder, Department of Integrative Biology, University of Colorado, Denver, USA; Anna Yachmennikova, A.N. Severtsov Institute of Ecology and Evolution of Russian Academy of Sciences, Moscow, Russia; Scott Yanco, Yale Center for Biodiversity and Global Change and Max Planck Yale Center for Biodiversity Movement, Yale University, New Haven, CT, USA; Elisabeth Yohannes, Department of Migration, Max Planck Institute of Animal Behavior, Radolfzell, Germany; Amelie Zeller, Skagen Bird Observatory, Birdlife Denmark; Christian Ziegler, Max Planck Institute of Animal Behavior, Radolfzell, Germany; Anna Zięcik, Akcja Carpatica, Rzeszów, Poland; and Cheryl Zook, National Geographic Society, Washington, DC, USA

*Correspondence:
walter.jetz@yale.edu (W. Jetz), tertitski@igras.ru (G. Tertitski), rwkays@ncsu.edu (R. Kays), and wikelski@ab.mpg.de (M. Wikelski).

https://doi.org/10.1016/j.tree.2021.11.011

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