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Biological Earth observation with animal sensors

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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 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.

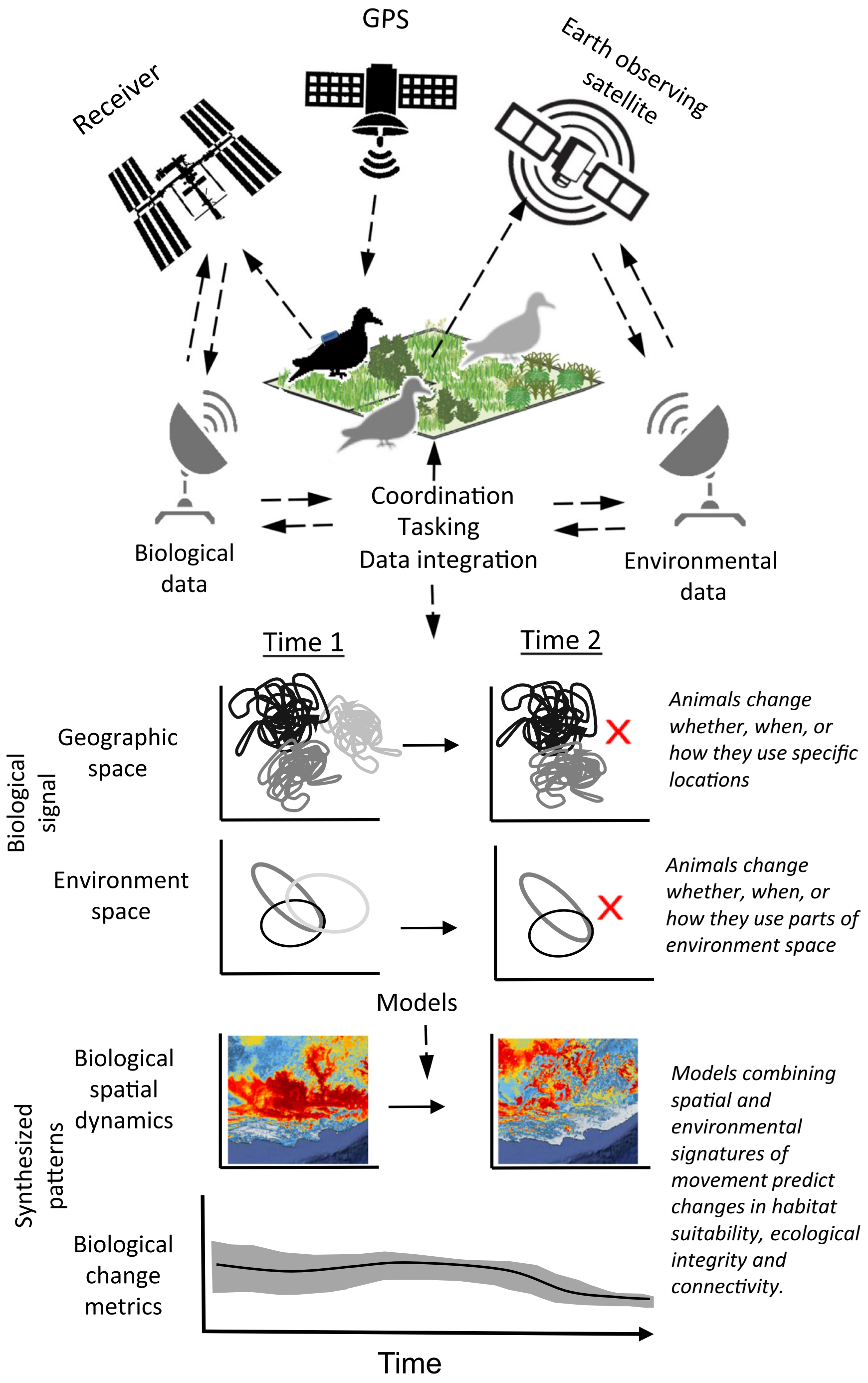

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Figure 2. Animal tracking-based Earth observation. Global positioning system (GPS) tracks of animal movements received via the space link are matched with remotely sensed environmental data. This enables the monitoring of animal use of geographic and 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.

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.

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