NextGen Natural History: New Technologies for Classical Natural History Questions

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Persistent questions regarding the identities of organisms and their relationships to environments have driven natural history through the millennia. Tools to investigate and record findings have changed, with recent innovations in genetic, tracking, and visualization technologies allowing naturalists new insights into long studied systems. These new approaches to classical questions – "NextGen Natural History" – have changed the content of the naturalist's field bag and enhanced the inherent wonder and appreciation in the discipline.

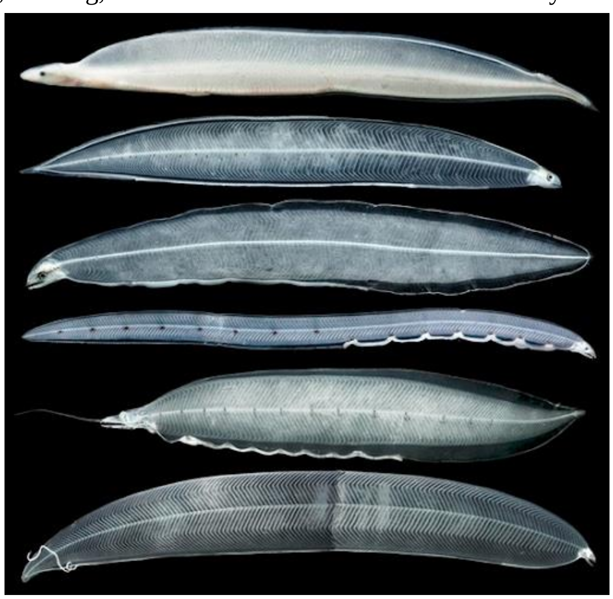

Figure 1. Larval eels can be connected with adult forms using genetic barcoding. (Image by Danté Fenolio.)

Natural history as a discipline is old, but it is not, and has never been, in stasis. Binoculars first came to be used in the field in the early 1900's (King 1955). SCUBA equipment came later, with popularization in the 1950's, but both are now accepted among the common tools used by field biologists and naturalists. It is our argument in this paper that natural history has always been a discipline of innovation, and that remains true today.

Genetic and Genomic Tools in Natural History

The majority of the world's organisms are challenging to work with. They live in difficult environments, often only coming into human range during a particular season or time of day – or not at all. This has made some basic natural history questions difficult to answer despite the persistence and curiosity of natural historians.

The power of genetic tools, developed over the last 20 years, is changing the questions that can be asked and answered by both professionals and hobbyists. The development of common gene regions as genetic barcodes has facilitated a suite of new tools and techniques. Use of barcoding technology to sample biodiverse environments has revealed the presence of "dark taxa" – abundant species that are not represented in traditional sampling strategies but are likely to be playing important and completely unknown roles in the ecosystem.

Genetic barcoding also provides insights into complex life histories and ecological interactions by serving as a "license plate reader" through which genetic identity can be established even in the absence of taxonomic identity (Barat 2016). This separation means that pelagic larval forms (Figure 1) can be connected with deep ocean adults by relying on sequenced biodiversity collections and large inventory projects (Plaisance et al. 2009, Templado et al. 2010), rapidly sequence gut contents to draw insight into trophic connections (Jakubavičiūtė et al. 2017, Casey et al. 2019), or even search for the presence of specific taxa in environmental samples of water, soil, or air.

Instead of digging into a coral reef matrix, scree slope, or aquifer, scientists can now also use environmental DNA ("eDNA"). For example, the DNA barcodes present in a few drops of well water are being used by the San Antonio Zoo's Mexican Blindcat Program to locate previously unrecognized populations of deep subterranean fishes, crayfishes, and salamanders and track the population dynamics of challenging species worldwide (Adams et al. 2019).

*Figure 2. The ecological relationship between deep-water anglerfishes (*Limnophryne spp.*) and their bacterial symbionts can best be understood through genetic tools. (Image by Danté Fenolio.)*

Whole genome sequencing, using much more genetic material, is also being used in creative ways to increase understanding of natural phenomena. For example, the DEEPEND Consortium is looking at the evolution of the symbiotic relationship between bioluminescent bacteria and deep-water fishes. With observations limited to trawled specimens, an understanding of the natural history of these taxa is greatly expanded by genetic approaches that allow documentation of the impacts of coevolutionary processes in extreme environments (Figure 2).

Genetic techniques can also be paired with machines that allow reaching environments previously inaccessible to the human body. The use of aerial drones and aquatic ROVs has expanded sampling strategies to include exhaled whale breath (Geoghegan et al. 2018), diverse photographic sampling (Christie et al. 2016), and both deep water and aerial environments (Thatje et al. 2008, Johnston 2019).

Remotely deployed devices (RDDs) have allowed close contact with species that would otherwise be impossible to see in life. For example, the first documentation of a live Giant Squid (*Archyteuthis dux*) in US waters and in the Gulf of Mexico was delivered by the MEDUSA device, developed and deployed by Dr. Edith Widder in the summer of 2019.

Not all "drones" are machines, and creative NextGen naturalists are using the keen senses of organisms to take biological samples. Examples of this are the use of honey produced by bees as a sampler of local flowering plants and phytophagous insects (Utzeri et al. 2018) and blowflies for vertebrate carcasses and scat (Lee et al. 2015). Another ingenious use is to analyze the diets of leeches (ingested DNA) to survey past and present forest communities (Siddall et al. 2019).

Letting the biology of the system reveal itself through these new molecular approaches allows the reconstruction of interaction networks not available to standard observational natural history protocols. In almost every situation, the level of partitioning demonstrated is remarkable (Casey et al. 2019).

Tracking and Motion

If finding and identifying organisms represent primary problems for naturalists, then following organisms through time or landscape is an escalation of this difficulty. These issues have been eased by the recent advancements and shrinking size of tracking technologies.

Approaches to tracking tree frogs vary; bulky radio transmitters or thread spools (Gourevitch and Downie 2018) represented significant challenges to the wellbeing of the animals. Passive integrated transponders ("PIT tags") and associated antennas allow for the short-range acquisition of location data from a microchip implanted in the body of an animal. Danté Fenolio and the San Antonio Zoo's Center for Conservation and Research are developing a project that will use PIT tag gate systems to follow cryptic predatory dragon frogs (*Hemiphractus*) in the Peruvian Amazon.

Banding birds gave naturalists a sense as to how huge of an undertaking bird migration is for both the birds and anyone attempting to follow their movements. The data and stories generated by banding hinted at the extremes of migration, which have been further elucidated by the development and miniaturization of new technologies in registering and transmitting data.

Transmitters, once restricted to large mammals and the largest of birds, are now small enough that they can track Arctic Terns (*Sterna paradisaea*) in real time as they migrate from one pole to the other, for multiple seasons (Egevang et al. 2010). Other techniques can be used with even smaller devices, such as light-level geolocators, which provide geographic placement of an individual organism based on light availability at a given latitude (Courmier et al. 2013).

Size-of-device still limits our capacity to study small organisms, but even this barrier may be falling through the development of transmission-and-relay networks specifically targeting animal motion. The "internet of animals" is a term used to describe several systems operating different technologies and different distances, including Motus, ICARUS, and MoveBank. These systems share an emergent ability to track even small organisms, relaying complex data to low orbit satellites or another tagged animal, such as a Turkey Vulture (*Cathartes aura*) circling overhead. Perhaps the most exciting element of these networked systems of tags is that they may relay not only geographic location but a host of other parameters such as weather conditions, health, or diet.

*Figure 3. Juvenile African Wild Dogs (*Lycaon pictus*) fight over and play with the head of recently killed Impala (*Aepyceros melampus*). (Image by David W. Shaw.)*

As an undergraduate, McKeon (1997) followed New World vultures around thermals of central Mexico in a hang glider trying to understand how they were using thermal energy to maximize available food resources. Dreelin et al. (2018) asked the same question of three swallow species in New York. In the twenty years between the two studies, the question remained largely the same, while technology advanced significantly.

Dreelin et al. (2018) were able to use a barometric pressure logger smaller than a dime (Shipley et al. 2018) attached to the back of the swallows to track how high the birds were going without joining them in the sky. They showed that each swallow species spent proportionally more time at different altitudes, revealing a basic ecological pattern of the aerial insectivore community. Similar technologies, combining geographic locality, altitude, and speed of travel, are being used to examine the movements of American White Pelicans (*Pelecanus erythrorhynchos*), revealing that the birds routinely get up to 30,000 feet and use thermal energy to cover huge distances (Davis 2018).

Optics, Photography, and Lenses

The ability of naturalists to use optical lenses to see and record information about the natural world has had a tremendous influence on the understanding of biodiversity. Starting with early microscopes and the adoption of binoculars by ornithologists, innovation in optical lenses have transformed the fields of ecology and natural history. Lens quality, sensor size, and image stabilization have added to the ability to capture both identity and behavior (Figure 3). Three tools now available to almost all naturalists on this front are trail cameras, "stacked" photographs, and cell phone cameras.

Trail cameras or camera traps were originally designed as security cameras for human habitations and businesses, and hunters quickly co-opted them to census target populations. With such a large group of people supporting the technology, camera traps have become a staple for studies of regional megafauna (cf., resources at eMammal).

Digitally stacked photographs utilize computer software to create images that are not limited by depth of field. This technique allows every curve, spine, and detail of an organism to be viewed simultaneously (Figure 4). The availability of these details changes the speed and effort involved in taxonomic descriptions and census efforts (Mertens et al. 2017).

The quality and availability of cell phone cameras has also changed the number of natural history observations. Operating on the principle that "the best camera is the one you have with you," the power and ubiquity of cell phones has made macro photography of small organisms a reasonable prospect for many casual observers, while pairing this function with the platforms and applications needed to create functional community science projects.

Information Sharing and Community Science

The combination of tremendous computing power, functional cameras, and access to taxonomic keys, field guides, and supportive communities via cell phones has resulted in sharing of natural history information in the last 10 years that is unprecedented and spectacular. eBird, the largest of the natural history community science and information sharing platforms, has over 500,000 contributors who have submitted over 50 million checklists and 700 million observations. Data of this scope and scale applied to natural history questions have never before been available. Direct conservation outcomes have resulted from the application of these data (Sullivan et al. 2017).

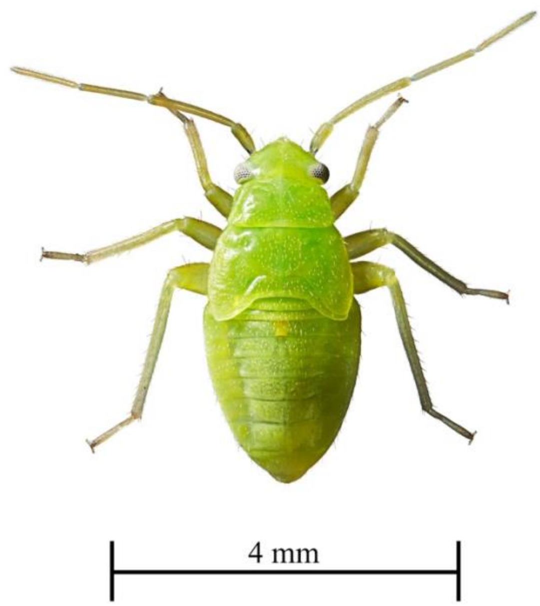

Figure 4. Modern macro photography facilitates identification and description of challenging subjects such as this immature Mirid. (Image by Zachariah Kobrinsky.)

And such tools are not just oriented toward birds. iNaturalist registers observations of all taxa, while many taxa have their own platforms aggregating information and giving voice to communities of enthusiasts who have never before had an opportunity to share their joy for the natural world with a global audience (Appendix 1).

Moreover, both eBird and iNaturalist have leveraged their open-access platforms to broaden the audience for participatory natural history. Machine learning techniques and "computer vision" software, combined with the vast repositories of digital media uploaded by participants to each platform, have enabled apps to capably identify numerous species from images (Barry 2016).

Now, any curious observer around the globe can snap a photo, upload it to Seek (iNaturalist) or to Merlin Bird ID (the sister app to eBird) and receive a suggested identification. In this sense, the digital technology of app-driven community science programs has not only enhanced natural history research and conservation, but it has also made engaging with nature more accessible to a significantly broader audience by lowering a fundamental, skill-based barrier to natural history participation.

The Role of Technology for the Future of Natural History

Who gets access to these new tools? New technologies come with prices that may limit the opportunity of many naturalists to use them. Optical tools such as telescopes and binoculars remained out of reach for all but the wealthiest individuals until "increasing availability of European optics made it easier to see birds" in the early 20^{th} century (Weidensaul 2007).

Modern birding is still associated with wealth, with the average income of American Birding Association members recorded as nearly three times the national average (Wauer 1991). Transition from luxury items to utility for both optical equipment and SCUBA was subsidized by early military adoption and production (King 1955, United States Naval Sea Systems Command 1991), and there are similar signs with the electronic technologies discussed here.

"Computing power available per dollar has increased fairly evenly by a factor of ten roughly every four years (a phenomenon sometimes called 'price-performance Moore's Law')" (AI Timelines 2017). As computer processing is the uniting factor of all of the technologies presented here, Moore's Law is relevant to our expectations of the adoption of these new tools, as is the ubiquity of computers in children's toys and home furnishings.

The technical ability to participate in current community science programs hinges largely on access to two things: smartphones to record data and cellular signal/Internet availability to upload data. Their rapid global proliferation in the 21st century has made access relatively feasible for many, even across the global tropics. However, these are still significant barriers to participation for those living in remote regions where these technologies have limited penetration, which are arguably the areas where biodiversity data are most sorely needed (e.g., the interior Amazon Basin), as well as use in marine environments, which constitute the majority of the planet.

While genetic analyses are dependent upon computer processing power, the collection and sequencing of genetic material is still reliant on biochemistry. Yet this barrier is falling as well, with the Centre for Biodiversity Genomics now providing LifeScanner, a free, limited opportunity for any individual to submit samples for genetic barcoding and identification. Jonah Ventures is now making beta-kits available to sample eDNA from local bodies of water. Digitization of museum records has been superseded by observation records from platforms such as iNaturalist and eBird, and these observations may be dwarfed by the power of new environmental sampling efforts like eDNA where one sample leads to hundreds of data points. While currently limited because of costs, the potential is great to monitor natural systems with far greater resolution than ever before in the near future.

The generation of technology presented here, like every generation of natural history tech before, provides useful tools to deepen our shared understanding of the natural world. The tools cannot replace the millennia-old character of natural history. The tools do not take you out to the wild places to sit quietly and watch. They don't ask the questions or find the answers. They extend a person's reach; however, it remains the job of our community to tell the stories, to access and protect the wonder and appreciation for nature that truly defines this discipline.

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Appendix 1. A sample of community science organizations with on-line resources.

Organization/Website	**Taxa/Subject**
eBird	Birds
iNaturalist	All macroscopic taxa
Pl@ntNet	Plants
eButterfly	Lepidoptera
eTick	Ticks
Zooniverse	All taxa
BugGuide	Terrestrial arthropods in North America
USA National Phenological Network	Climate, ecology, and timing
Reef Environmental Education Foundation	Coral reef biota and health