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More Than Bells & Whistles: A Perspective on the Role of Technology and Innovation in Expanding the Conservation Toolbox

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On a hillside not far from the coast of Jalisco (Mexico), I slowly made my way through the dense understory of a tropical dry forest. It was the mid-1990s, and I was part of a team of volunteers collecting population data on a unique carnivore community in the country's Agave State. The Biosphere Reserve was (and still is) habitat for bobcats and coyotes, ocelots and jaguarundis, foxes and coatimundis, and of course, jaguars and pumas—the real reason the younger me was there. One of about five or six volunteer field assistants, every morning I set out in a new direction as the group rotated activities, each day hoping I was the one who would return with the newest ecological insights. That morning, I had already hiked seven kilometers from our research station across very uneven terrain. My objective at that moment was to check a new sampling unit in an ecological study: the latest advancement in wildlife survey technology. Rounding a trail bend, my eyes fell to the fresh animal tracks emerging from a narrow path in the forest. They were fresh jaguar tracks; of that, I had no doubt. Looking up, I saw the unit was only about 40 meters away, and the tracks led right to it. Flush with renewed enthusiasm as I approached, I couldn't help but notice how out of place this plastic contraption was among the dusty thorns and fallen leaves.

Far from stealthy, this new system was quite an ingenious design, one that was increasingly being used to monitor mammal populations around the world. Mounted trailside on a 12 meter tall tree with smooth bark was a camera in casing so clunky, it appeared ready for deep sea exploration. Under the camera sat a rectangular digital transmitter with a blinking red indicator light. Across the trail was a receiver with a window displaying the large, analog numerals typical of the day's digital technology, its alignment squared up perfectly with the transmitter. These integrated devices were becoming widely known by biologists as an "active camera-trap," a sampling platform that could record the passage of an animal remotely if it broke or "tripped" the beam between the transmitter and receiver (Kucera and Barrett 1993; Sweitzer et al. 1996; Hernandez et al. 1997a,b; Kucera and Barrett 2011). Placed on trails in just the right spot, camera-traps could finally yield photos of the most cryptic, endangered, or low-density mammals in far-flung tropical forests that too regularly eluded wildlife biologists (Griffiths and van Schaik 1993; Karanth 1995). Because each photo was an unequivocal record of that species in time and space, combined they constituted the key ingredients of a successful population or community-level ecological analysis. That was the prevailing theory at least. As I removed the roll of film and swapped it with a fresh undeveloped cartridge, careful to wipe off any dirt, my mind turned to the possible images that sat unexposed in my hand.

Back at the reserve's headquarters later that afternoon, I was reluctant to throw my film into the community heap forming on the table. I had put it in a clearly marked bag of course, to indicate which camera-trap the film had come from, so there was no danger it would get lost in the shuffle. Having seen the tracks earlier that morning, I was confident that my camera-trap recorded something special. My anxious glances to the pile must have given me away, because one of the principal investigators right then asked me if I wanted to accompany them the next day to process the film. Despite a 200 km round-trip across rural Mexico (or because of it?), I was game. I just had to be among the first to know.

The next day, we were off to pick up supplies and develop the film. I sat in the back of the 4WD pick-up truck, steadying myself during hairpin turns along the road's cliffside. Early commercial camera-traps were as cost-ineffective (e.g., US $500–600) as they were unwieldy (Cutler and Swann 1999; Swann et al. 2004), and since each of the 20 or so units burned through about 6–8 batteries every two to three weeks, batteries were at the top of our shopping list. A few hours before sunset we stopped to retrieve the photos, ready to head back. As I recall, I snatched the small Kodachrome folder of 4" x 6" photo prints from the counter and got halfway back to the truck in the time it took me to say thanks to the store owner.

We had hardly pulled the truck forward before I was snapping photo prints onto the plastic dashboard console in front of me, one atop the other. The first photo was of the trailside directly in front of the camera, the dry forest in the background and small, dense thorn scrub bushes and grasses at the forefront. No animal in the frame—the photo was empty. Confused, I quickly snapped down another photo on top of that one. Same thing—empty. So was the next photo. And the one after that. Surely we recorded something, I thought. My heart began to sink after I made it through about three-quarters of the roll and then, Photo 32. Taking up most of the frame was the distorted muzzle of some creature, its left eye completely out of focus in the top right corner. A curious coyote, no doubt; a contention further supported by the jagged teeth marks that would later be noted on the camera's otherwise smooth external plastic casing. I noticed the date and time across the bottom of the photo in big orange digital numerals, which indicated it was taken the evening before I retrieved the film. Quickly flipping through the last four photos—one of which contained the tip of the coyote's tail—I reluctantly accepted that the camera ran out of film before my jaguar walked past it on the hillside early that morning.

To say that this experience was common for early camera-trappers would probably be an understatement. All that effort, both in the field and out, for so little return. Although eventually my own camera-trapping efforts would lead to photos of not only jaguars, but more than a hundred species of carnivores on four continents, I racked up many kilometers both on foot and by car to develop photos of nothing. I was part of a small but growing group of early users passionate about the potential and promise of these devices to survey rare and cryptic mammals, which too often differed from the reality of how they functioned on the ground. Rarely did I stop to think that commercial camera-traps weren't really made for us, i.e., wildlife and conservation biologists conducting scientific research. They were largely marketed as "game cameras" or "trail cameras" for hunters (Meek and Pittet 2014) who maybe only had need for one or a few, whereas scientists needed a minimum of 20, 50, even 100 of these cameras if we were to produce worthwhile science. Nor did I think about what this reality meant for end users deploying the device "off-book," trekking them through some of the most unforgiving environments on the planet. If units failed or operated otherwise encumbered, thousands of precious dollars of investment in equipment and logistics could be for naught.

I'm happy to say that camera-traps went on to ultimately transform the study of elusive mammals and other vertebrates, becoming one of the most powerful and innovative tools on the frontlines of conservation monitoring (Hance 2011; O'Connell et al. 2011). Today there are more "trail camera" or camera-trap models, with more features and accessory applications, than one can possibly imagine, a fact that sometimes makes choosing the proper unit for your study a dizzying affair (Swann et al. 2011). As a veteran scientist still using camera-traps 25 years later to build occupancy and spatially explicit wildlife population models, it is an unwitting part-time job for me every year to stay on top of the latest features and values being offered. Of course, these days nearly all commercial camera-traps are digital infrared models with the capacity to take thousands of photos and batteries lasting four to six months. And the best models among them are unlikely to miss anything walking nearby, firing off 10 photos or 10 seconds of video before an animal can leave the frame. But the evolution of the camera-trap brought with it challenges both familiar and novel. For example, instead of a full roll of film with little to show for it, memory cards can now store thousands of photos… of mostly nothing. With that revolutionary capacity, the unsettled question remains of how best to process and sort hundreds of gigabytes of photos and video.

One emerging answer is through the use of automated image and pattern recognition software (Meek et al. 2019; Green et al. 2020). Machine learning, or first generation artificial intelligence, which has the potential to draw from diverse training algorithms and deep data reference libraries, can not only filter out empty photos, but can correctly identify the species present in a photo or video (Meek et al. 2019; Green et al. 2020). Part science fiction and part reality, the day when the two become one—at least for additional practical uses of this technology—is not far off.

The evolution of the camera-trap is only one progressive technology story to be told in the diverse world of biodiversity science and conservation. Applications for accurate, non-military use of Geographical Positioning System (GPS) Technology for example became broadly possible around the same time as early camera-traps were proliferating in wildlife research and conservation [Source: National Archives and Records Administration, U.S. Global Positioning System Policy]. One consequence of this was an explosion of additional applications for monitoring of wildlife populations and other environmental variables. Reasonably accurate Global Navigation Satellite Systems (GNSS), which today can mark a location to within meters, contributed to the surge in popularity of desktop Geographical Information Systems (GIS) software (e.g., Booth 2000). When combined with parallel advances in remote sensing capacity, high accuracy mapping of critical habitats, landscape features, and biodiversity hotspots became possible (e.g., Biging et al. 1995; Gould 2000; Horning et al. 2010). In this issue, Galante et al. (2020) provide a useful introduction for students on how to use QGIS, a free open-source GIS program, to model suitable habitat for a cryptic mammal species.

Eventually, more satellites enabled a broader GNSS network, and a proliferation spatial analytical tools for terrestrial environments led to more options for precision conservation planning (Wang et al. 2010; Rose et al. 2015). A similar suite of software tools, including novel applications like SeaSketch, are now available to those planning the conservation of marine protected areas and sustainable fisheries (Gosnell et al. 2020, this issue). These advances in GNSS and GIS had similar consequences for telemetry and tracking technology, permitting breakthroughs in the study of species movements both large and small. Like camera-traps, tracking devices today have countless features and improvements. Just a sample of these include: longer battery life; spatial data in real time via different satellite networks; an ability to withstand extreme variation in temperature and pressure; and tiny devices that can even be tethered to a bumblebee (Kuhn et al. 2009; Hagen et al. 2011; Recio et al. 2011; Dressler et al. 2016; Taylor et al. 2017).

Imagine now, the power of further cross-pollinating these advances with other proven and promising tools: for example, combining advances in tracking and GIS with the capabilities of Unoccupied Aerial Vehicles (UAVs) (e.g., Ivosevic et al. 2015; Christie et al. 2016; Horning 2018) and LiDAR (Light Detection and Ranging) remote sensing – a technology that has revolutionized our ability to map the surface of the earth (e.g., Davies and Asner 2014; Garabedian et al. 2017). What emerges is a set of effective and innovative tools that can facilitate wildlife survey and research prospects in new habitats. Such an integrated system can also simultaneously track the movements of multiple species while monitoring daily deforestation and mining activities. With the help of SMART (Spatial Monitoring and Reporting Tool) data, it could also lead the enablement of effective anti-poaching responses, and predict where those same resources are needed tomorrow (Marvin et al. 2016; Krester et al. 2017). Advances in automated acoustic monitoring might ultimately hold similar potential for conservation law enforcement (Astaras et al. 2017; Hill et al. 2018). For the past decade, acoustic sensors have been used successfully to survey threatened and endangered bats, frogs, primates, and birds (Digby et al. 2013; Heinicke et al. 2015; Russo and Voight 2016) and are also being used to document changes in the expanse and intensity of anthropogenic noise (anthrophony) in urban, wilderness, and marine landscapes, enabling scientists to better understand noise impacts on biodiversity (Nowacek et al. 2007; Buxton et al. 2017; Gibb et al. 2019). The exercise by Clark et al. (2020) in this issue highlights acoustic monitoring technology and introduces it to students in the context of urban bats.

The data being collected by these technologies are leading to a new challenge, one the scientific community hasn't faced previously: what to do with all these data?! Having finally crossed the threshold of "big data" in ecology, we hope that our innovations to store, process, and analyze all of it will be equal to the task—perhaps by enlisting some combination of cloud-based servers (Arts et al. 2015; Chapron 2015), or machine learning (see Peters et al. 2014, as well as work being done by the Center for Biodiversity and Conservation on Machine Learning projects). Of course, it is critical that we also ensure such data is used and shared responsibly and ethically (Rambaldi et al. 2006). Conversely, there has been an unfortunate and corresponding decrease in financial investment in the most timeless repositories of taxonomic data: the great museums and herbariums of the world (Kemp 2015; Editorial in Nature 2017). Our new emphasis on big data should not come at the expense of hallmark taxonomic and systematic institutions, whose collections constitute the bedrock of evolutionary and ecological disciplines. On the contrary, progress in conservation has depended on, and will continue to depend on, discoveries at these institutions for years to come. Rather than being in opposition to big data, what if those collections became big data? What if we created a three-dimensional digital universe for earth's biodiversity, based on museum collections?

Digital libraries hold the same promise for the incredible molecular advances we've seen in recent decades as they do for natural history collections. As with many innovations, the development of powerful genetic tools for biodiversity research and conservation were derived from advances in the human health arena. What emerged was the field of molecular ecology, a discipline that aimed to evaluate the genetic relationships among populations and entire species, and the changes to its tools happened very fast. As the discovery of Taq polymerase gave rise to more cost-effective DNA amplification via Polymerase Chain Reaction (PCR) (Saiki et al. 1988), so did the initial popularity of allozyme electrophoresis and mtDNA haplotype analyses yield to analysis of short, repetitive nucleotide sequences of DNA known as microsatellites (Litt and Luty 1989; Richard et al. 2008). A technique to recover and amplify low-quality, degraded DNA from sloughed epithelial cells in the digestive tract (Albaugh et al. 1992) made it possible to sample low-density species noninvasively, making remote genotyping and sex identification of individual animals via scat samples possible and further proliferating the number of microsatellite studies (Taberlet et al. 1996; Reed et al. 1997; Wasser et al. 1997). Hardly more than a decade later, the increasing use of hundreds to thousands of Single Nucleotide Polymorphisms (SNPs) offered greater genetic resolution than microsatellites (Morin et al. 2004), and eventually began to supplant them in conservation and ecological genetic studies. Parallel advances have facilitated accurate species identifications via low concentrations of environmental DNA (eDNA) gathered from the water in which those organisms swim (Jerde et al. 2019), including a rare, apex predator in the open ocean (Truelove et al. 2019). New eDNA techniques are promising for informing conservation management; see the exercise by Douglas et al. (2020) in this issue. Whole genome sequencing of individual non-target organisms, formerly costing millions of dollars, is also now cost-effective (Ekblom and Galindo 2011; McMahon et al. 2014), and a new device has emerged that can now help one do it all on the go (Lu et al. 2016). Most recently, the wonder and risks of new genetic engineering tools like CRISPR-Cas9 (Jinek et al. 2012) have intensified the global debate about genetically modified organisms, even as they potentially represent the most effective method devised so far to control invasive species.

Looking to the future, I am both excited and optimistic, as the prior examples are just a sample of the innovations relevant to safeguarding earth's biological diversity. We are standing on the precipice of some very formidable challenges. Extinction and climate change are inescapably entwined, and loom large in the Anthropocene. For countless species, their prospects are worse than ours. Yet, even as humanity grows closer to a threshold of runaway warming, global habitat change, and escalating conflict with fellow species, we also grow closer to the point that could tip balance the towards realizing a sustainable planet. No, of course technology alone won't save the world. The will and commitments of our governments and institutions, responsible consumption, behavior, and corporate governance, and a socio-political climate that acknowledges the importance of empirical evidence, all have very important roles to play. But the potential for parallel, advancing technologies to converge, mutually enhancing their respective capacities to tackle climate change, illegal wildlife trafficking, deficits in biodiversity monitoring, human-wildlife conflict, global land use change, sustainable food production and food security, and ultimately the earth's extinction crisis, is nothing short of enormous.

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