Trends in Ecology & Evolution

Review

Emerging Technologies to Conserve Biodiversity

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Technologies to identify individual animals, follow their movements, identify and locate animal and plant species, and assess the status of their habitats remotely have become better, faster, and cheaper as threats to the survival of species are increasing. New technologies alone do not save species, and new data create new problems. For example, improving technologies alone cannot prevent poaching: solutions require providing appropriate tools to the right people. Habitat loss is another driver: the challenge here is to connect existing sophisticated remote sensing with species occurrence data to predict where species remain. Other challenges include assembling a wider public to crowdsource data, managing the massive quantities of data generated, and developing solutions to rapidly emerging threats.

Trends

Conservation requires methods to identify species and to identify, locate, and track individual plants and animals. These methods have become better, faster, less intrusive, and cheaper. So, too, has remote sensing that now allows detailed and frequent assessments of species' habitats and how human actions are changing them.

Even the best technologies to mark individuals may pose unacceptable hazards for endangered species. Creative approaches find new, non-invasive alternatives.

Crowdsourced data are becoming the dominant source of information on species' distributions and new approaches are solving the problems of reliability.

The most important trends are progress in technologies that are appropriate to the often remote and low-technology environments in which frontline conservation actions unfold and the inclusion of previously unused communities who might contribute essential data.

The Challenge and Opportunity of New Technologies

Human actions are exterminating species at exceptional rates and threaten large fractions of species across many taxa [1]. Over most of the land [2] and oceans [3], humans have eliminated top predators and large-bodied species, massively changing the remaining ecological communities [4,5]. Finally, although there has been impressive progress to protect more land and ocean, the range of ecosystems protected is uneven [6]. International consensus affirms the severity of these problems [7] and demands solutions.

New technologies have the potential to help with these solutions. We will review the development of these technologies only briefly because there are excellent and recent reviews of advances elsewhere. Our aim is merely to capture the pace and scope of their development and to provide examples for further discussion. We concentrate on emerging issues that could expand or limit solutions for species conservation.

Individuals and Their Movements

The past decade witnessed unprecedented expansion in technologies providing data on where individuals are and on their movements [8]. Tracking individuals has moved from using bulky and expensive radio-collars to smaller satellite-based devices and even to innovative non-invasive approaches. Technology provides new opportunities through informative compounds from the tracked animal's tissue (such as isotopes and genetic material) and even directly from remote sensing.

Location Data

Obtaining locations of species has also shown impressive improvements. Digital camera traps have replaced film-loaded ones, greatly expanding our abilities to detect rare or secretive species. Satellite-borne cameras can detect and monitor some animals in open habitats. Examples include using Landsat 30 m resolution satellite data to detect the presence and size

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of emperor penguin colonies in Antarctica [9], and Geo-Eye 1.65 m resolution satellite data to estimate population sizes of elephants, wildebeest, and zebra [10,11].

Airplane surveillance has monitored wildlife for decades, but unmanned aerial vehicles (UAVs or 'drones') capable of taking photos and videos could provide better, cheaper, and timely information compared to manned aircraft surveillance or satellite images.

Databases on species occurrence have also expanded rapidly. For example, the Global Biodiversity Information Facility (GBIF) has 420 million records and 1.45 million species names (Global Biodiversity Information Facility; www.gbif.org), while Tropicos (www.tropicos.org) has 4.4 million plant records. Records enter these databases via four main routes: museum and herbarium specimen collection, DNA sampling, crowdsourced observations, and remotely sensed images or sounds.

Natural history collections detect species at a specific location, including the identification of these detections. These are archived in museums before being digitized and incorporated into GBIF. Museum specimens require considerable expertise and expensive curation but offer the best evidence for the presence of a species, and for subsequent morphological, genetic, or isotopic research.

DNA libraries have been built for 2000 endangered species and an additional 2 891 971 specimens, making up 192 480 species (The Barcode Library, Barcode of Life Data Sytems; http://ibol.org/resources/barcode-library/). Both these sources limit the pace and scale of what can be collected, however [1].

Image-recognition algorithms are being applied to pictures of species. For example, the Smithsonian LeafSnap iPhone application (http://leafsnap.com) uses image recognition to identify Eastern North American tree leaves. Automated identification of bird or bat calls has been an active area of research for over a decade.

The most rapid advance in collecting location data comes from smartphone-wielding citizen scientists. For example, eBird (www.ebird.org) became an international depository in 2010 and already has >100 000 observers and >100 million observations. It permits fine-scale mapping and month-by-month changes in the distribution of some species. When photos or other vouchers are lacking, additional care is needed in vetting observations.

Remote Sensing of Environmental Drivers

Finally, there is our ability to monitor the environmental changes that cause species declines or, in the case of invasive or introduced species, their expansion. Responding to a request from the conservation community, NASA provided free Landsat imagery for 1990 and 2000 only in 2001. Now, much higher resolution imagery is freely and widely available, if not globally, that was usually first developed for consumer markets. Unprecedented amounts of data are becoming available from constellations of cubesats. (These are low-cost, small satellites that harness consumer technology rather than bespoke technologies and that have exceptional power in constellations. They are an alternative to a single, powerful but – by the time it reaches space – sometimes out-dated satellite.) They look to revolutionize medium resolution imaging through global, daily coverage (e.g., Skybox/Google, Planet Labs) and are being launched by an increasing number of countries and private companies [12–15]. Between 2012 and 2027, member agencies of the Committee on Earth Observation Satellites (CEOS) will operate or plan to operate 268 individual satellite missions [15]. Recently, the European Commission agreed to make the new Sentinel satellite data freely available. Drones are increasingly sophisticated and affordable providing unprecedented coverage of environmental changes [16].

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Emerging Issues

It would be trite to notice that these and other improvements will continue, that technologies will become cheaper, faster, easier to use, and so on. What follows is our selection of the difficult conservation questions that emerge. First, which technologies are on a cusp, in other words where might improvements make dramatic changes for species conservation? Box 1 provides three suggestions.

Second, where might conventional technologies remain problematic for conservation despite continued improvements? For example, ecologists have used tracking technologies for decades. The hardware for these technologies is getting smaller, yielding more frequent, more accurate fixes of locations, and this will surely continue [8], adding more types of data [17,18] or data on more species. Even for common species, factors may favor non-invasive monitoring techniques. Specialized miniature electronics are typically expensive, with additional monthly network charges for satellite or cellular data accounts [19]. Physically capturing animals is difficult, expensive, and may invalidate the data collected [20]. For endangered species, even the least-intrusive attachments may pose a risk to their small populations and be unacceptable to the researchers or those who issue them permits. Box 2 explores the scope and variety of non-invasive techniques to identify at the individual and species level, and can derive data from animal traces without disturbing them (see Figure I in Box 2).

In remaining sections, we discuss six further issues that require attention if technologies are to achieve their full potential for species conservation. (i) Box 3 addresses the quality of the data from crowdsourcing – an issue of particular concern to conservation where the species of interest are rare and sometimes unfamiliar. (ii) How can we handle the quantity of data that new methods now yield? What are the challenges in organizing the massive data acquired, especially

Box 1. Where Might Improved Technologies Make the Most Difference?

We pick three examples. Our first is genetic barcoding. It now identifies a species for US$1 per sample from a small, but unique, DNA sequence [59]. For the great majority of unknown species in groups with few taxonomic specialists, this will surely become the predominant method of discovering new species or surveying their communities. Even cheaper identifications of single species and batches of species will surely change the pace of species description and our knowledge of where rare species live. It raises the controversial idea that many species may become known by a number derived from barcoding and not – or not only – from conventional descriptions [60].

At present, the extensive efforts to set conservation priorities, from local to international scales, typically rely extensively only on well-known amphibians, birds, and mammals [1]. Cheap barcoding offers the potential to map priority areas for species conservation for far more taxa, and thus makes the process more inclusive.

Second, remote sensing and its continued improvements are familiar, but detecting species remotely from satellites is not. In the future, we are likely to see daily coverage of 1–2 m resolution satellite data. That resolution, however, is not sufficiently fine to count even large-bodied species, such as elephants. At present, geographically large-scale surveys of large-bodied species, such as elephants, from helicopters or fixed-winged aircraft, are extremely expensive. Modest improvements in the resolution of satellite images might open up routine assessments. Moreover, they might do so in areas where existing surveys are difficult or dangerous. A particular challenge will be how new software can automatically process the vast amounts of data obtained.

Finally, drones, accompanied by visible and infrared multispectral sensors with 10–24 megapixel mirrorless cameras, associated software, and internet connectivity, increasingly offer better information at a cheaper cost compared to airplanes and satellite imagery. Low-altitude drones flying below 150 m and equipped cameras are capable of taking both still photos and videos. Drones range from basic models under $2000 to sophisticated multisensor models for six figures of more. Drones are used in several biodiversity applications, including monitoring of forest fire [61], identification of floristic biodiversity of understory vegetation [62], identification of standing dead wood and canopy mortality [63], monitoring invasive species, pests, weeds, and diseases [64], and aerial monitoring of animal species [16,65].

The drawbacks include flight restrictions, hardware depreciations, and a very steep learning curve in both data collection and interpretation. For some important uses we discuss below, improvement in their sophistication and how long they can spend in the air would be a dramatic advance.

when rare species will likely contribute only a tiny fraction of those data? (iii) Box 4 asks: given the ubiquity of smartphones, how can we bring in a wider group of participants to monitor biodiversity, recognizing that these participants might also be key stakeholders? (iv) How might technology help to prevent poaching, which is a major cause of species endangerment? We will argue that the challenge is to develop appropriate technologies, not necessarily the most advanced ones. (v) We then address perhaps the main cause of species endangerment: habitat loss. Here the challenge is to combine existing technologies and databases. Both continue to make rapid improvement, but connecting them is difficult. (vi) Finally, how can we increase the pace of innovation and integration as other rapidly developing technologies have done? Failure to respond quickly may doom species to extinction.

Data Collection, Integration, and Analytics

Processing the millions of photographs typical of large-scale camera trap monitoring is one of many examples of challenges that require sophisticated data-management tools [8]. The challenge is particularly acute for conservation where the species of interest are rare and observations few amid a flood of other information. Most image processing is still carried out manually, for example, using citizen scientists to classify 1.2 million camera trap images from the Serengeti National Park [21]. Computer vision tools and crowdsourcing are starting to be integrated into the data workflow to add efficiency [22]. Several new efforts are testing paths that are completely automated, relying on remote sensing to detect species and image analysis to identify species.

Box 2. The Promise of Non-Invasive Monitoring

These are a few examples of techniques that illustrate the broad score of methods to monitor individuals and species that show particular promise for species that are threatened and where invasive techniques may be prohibited (Figure I).

The footprint identification technique (FIT): translates millennia-old tracking practices. Using a customized script in JMP data visualization software (www.jmp.com), digital images of footprints are optimized and derived morphometric variables fed into a robust cross-validated discriminant analysis [66,67]. FIT classifies by species, individual, sex and age-class at >90% accuracy and has been adapted for species from mammalian herbivores and carnivores [66,68]

Scent-detection dogs: have been able to identify free-ranging individual Amur leopard [53] and grizzly bear [55] from natural traces in their environment. The canine nose and olfactory cortex may be five orders of magnitude more sensitive than their human equivalent [69].

Pelage or skin patterns: have long been used to identify individuals, usually from camera-trap images. However, manual identification of the large numbers of images generated is challenging. Computer-vision techniques have the potential to automate this process [70], with some successful examples allowing the identification of individuals [71] and species [38] based on coat patterns. Patterns of facial vibrissae are also unique to individuals and can be used for identification where images can be captured at the correct orientation [72]. Where no distinctive body patterns or markings exist, camera-trap imaging is generally ineffective [73]. Improvements in image resolution and multispectral capture combined with morphometrics could address this challenge. Broadly, these and other biometric approaches to individual and species identification are developing rapidly as multidisciplinary collaboration gains momentum [74].

Infrared sensors: provide the potential to identify individual animals either at traditional camera-trap stations; from sensors directly connected to smartphones; or aerially from drones. Multispectral sensors are being trialed for their ability to identify aerial-census species from pelage reflectance characteristics. Increasing sensor sophistication and deployment by citizen scientists, recreational visitors, or indigenous expert trackers could hugely augment both the quality and volume of data collected.

Acoustic techniques: many species have individually distinct vocal features [75], but more work will be necessary to collect and analyze these in ecologically-relevant ways. Promising advances have come from new algorithms [76], for example, illuminating social affiliation in killer whales through individual vocal signatures [54].

Non-invasive genetic sampling: individual identification from DNA in hair, feces, and saliva will be a valuable monitoring tool as the number of loci available for individual identification increases and genotyping errors are reduced, as studies for the identification of individual Amur leopards [53] and grizzly bears [56] have demonstrated.

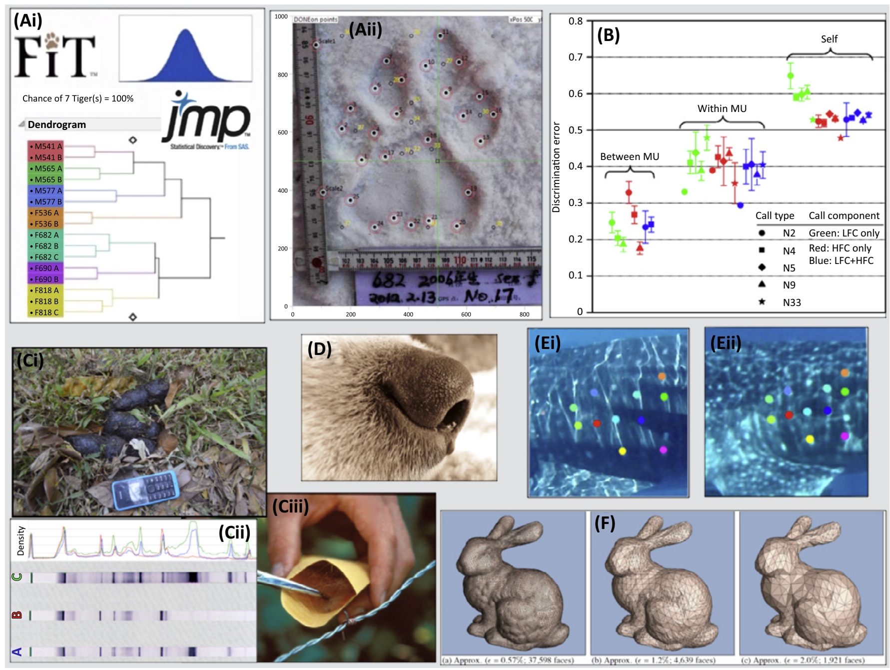

Figure I. Examples of Non-Invasive Techniques for Individual Identification. (A) The footprint identification technique for species, individual, sex and age-class identification (www.wildtrack.org) [53]. (B) Identification of individual killer whales and their social affiliation in matrilineal units determined by sonograph (credit: Anna.Mcgregor@glasgow.ac.uk) [54]. (C) Sources of environmental DNA [55], feces (Ci) and hair (Ciii), and individual DNA fingerprinting output (Cii) where Ci and Ciii are related. (D) Canine olfaction for the identification of individuals from feces, urine, and hair (credit: Working Dogs for Conservation; www.wd4c.org) [56]. (E) Automated spot-pattern identification showing the same whale shark from two different angles [57]. (F) Generation of 3D mesh nets at three different resolutions showing the potential for morphometric analysis [58] (credit: M. Eck).

Ubiquitous devices and people connected to cloud computing systems with machine-learning capabilities will revolutionize the types of data we collect for conservation. The hierarchical structure of data flows, from local data collection to their inclusion into databases like GBIF, will only increase with the adoption of new technologies. No single tool will allow monitoring multiple different species and in diverse landscapes. Instead, a toolbox of technologies around a dedicated analytical pipeline will allow the conservation community to extract insights at unprecedented scales.

There will be difficulties. Conservation must confront the same challenges with 'big data' that are currently causing difficulties in the consumer and enterprise markets [23]. As experience with GBIF shows [24,25], assembling data from disparate providers, including national governments, museums, and citizen scientists, can present significant technical obstacles around data quantity, quality, integration, and information extraction, and the cost, robustness, and ease of use of technology solutions.

The problems inherent in big data are minimized by storing fewer of them. Most are of little use without context-relevant information [26]. Increasing computational power on small devices means that information can be extracted on-board [27]. For instance, if a remotely deployed camera is to detect poachers, it need not store or send every image if it can run human recognition algorithms and communicate only when there is activity to report. Citizen science

Box 3. The Challenges of CrowdSourced Observation

Observations have shortcomings. Identifying other than a few well-known plant and animal taxa requires the skills of a small community of taxonomic specialists or localized naturalists. Likewise, the isolation and examination of DNA characters requires molecular biology skills and equipment currently beyond the reach of most conservation practitioners. How might technology overcome the challenges of species identification?

Detections made by eBird and similar programs do not produce vouchered collections or images that one can share or independently verify. In the eBird model, observer credibility accumulates as individuals claiming unusual sightings back them through a manual review process. The success of eBird testifies to the strength of the birding community it leverages. That community has extensive experience of vetting the usual observations that most interest those concerned with conservation. This limitation prevents the application of its style of citizen science to organisms that are harder to detect or identify.

The iNaturalist model relies on crowds of citizen scientists to scale both the detection and identification of species from photo vouchers. Apps such as iNaturalist (www.inaturalist.org) allow division of labor between amateur observers uploading mystery field observations from smartphones and experts who catalog the photos provided. Such cooperation now produces high volumes of quality data for diverse taxa. For example, iNaturalist has already logged over a million records and has become the preferred app for incorporating crowdsourced data into national biodiversity surveys in Mexico and elsewhere. The Reef Life Survey generates similar advances for marine biodiversity (http://reeflifesurvey.com).

Unlike DNA, widely-available smartphones can capture, digitize, and electronically share morphological characters. Here, new technologies are revolutionizing images and how we can use them to identify species. A Google image search serves as an analogy. The mosaic of images returned by your Google search for 'red ball' makes use of two primary tricks: machine image recognition and human crowdsourcing.

The crowdsourcing piece of your 'red ball' image search is subtle. Google includes pictures that might not look to its image-recognition algorithms as resembling red balls at all, but instead images that thousands of other people clicked upon in making the same search. Crowd actions indicate that these images pertain to red balls. Crowdsourcing can similarly work for species identification. If a hundred people agree that a particular image is of a bobcat, we can be confident in the identification. Enabling the crowd to communicate through social networking technology can help localized naturalists and taxonomic specialists lend their expertise to the large numbers of images that others produce. iNaturalist exemplifies a species identification tool relying on image sharing and social networking technology to crowdsource species identification.

platforms could also engage in new ways with new groups (such as indigenous communities ([28], see below) to increase the efficiency of data collection and accuracy. For example, one might send volunteers to locations that likely harbor an endangered species, based on probabilistic models. Equally, probabilistic models themselves might be generated by unexpected observations gathered opportunistically.

However efficiently data are collected, storing and provisioning data at the scale envisaged can quickly become unmanageable without highly specialized data management solutions. Opening those data to a global community from different educational and cultural backgrounds imposes technical challenges in designing software, maintaining interpretable application program interfaces, and reliably available and secure internet servers [29]. There are additional challenges of including scientists wary of sharing their data with others [30], and of privacy concerns to keep sensitive information from criminals. For example, iNaturalist obscures the observed locations of endangered species except for authorized users.

None of the obstacles presented by biodiversity data are insurmountable. Nevertheless, most of the technologies we have described are in active development and were not invented with environmental applications in mind. For instance, there are constant trade-offs between the size and power of a device and its data collection, storage, and communication potential. Many devices are for environments with constantly available power and connectivity. Modifying devices to collect biodiversity data in harsh, un-instrumented environments often requires sophisticated skills and considerable financial resources. Recruiting these skills and resources will be crucial for realizing a technology-enabled revolution in biodiversity conservation.

Box 4. Acquiring Unconventional Data From Previously Disengaged Communities

Participants in biodiversity surveys are still predominantly educated citizen scientists or amateur naturalists. More data – and data collectors – are essential.

Cell phones have moved societies beyond traditional infrastructure barriers. Their spread is particularly rapid in undeveloped countries (Figure I). Estimates suggest that mobile subscriptions in Sub-Saharan Africa will increase from 551 million in 2013 to 930 million by 2019, approaching global rates of penetration at 92% [77]. The power, capacity, and connectivity of phones have improved data quality, created new environmental sensors, new ways of streamlining data collection and management, and expanded the pool of data collectors and analyzers. They can identify centers of political corruption, for example. They could facilitate much broader participation in conservation and engage two currently barely used groups: tourists and indigenous communities.

First, eight billion recreational visits are made annually to terrestrial protected areas alone [78]. Tourist-based photographic surveys in Kruger National Park contribute to African wild dog and cheetah surveys [79]. Second are indigenous communities and experts, for example, trackers with traditional ecological knowledge (TEK) [80]. Studies have favorably compared survey data from TEK experts with ground sampling in the quality of their recorded data [81]. Inexpensive tablets facilitate community mapping of natural and cultural resources in and around Tanzania's Gombe National Park [82]. They allow 'citizen scientists' to collect data on land-cover change in India's Western Ghats [83].

The challenge is making technology accessible. In the hands of all stakeholders, even basic smartphones provide a wide range of conservation-relevant data. Rural communities can record incidents of human–wildlife conflict, monitor habitat, or anonymously report intelligence information to authorities. Broader participation would increase the volume of data collected and afford opportunities to engage local communities, thus resulting in long-term conservation success [84].

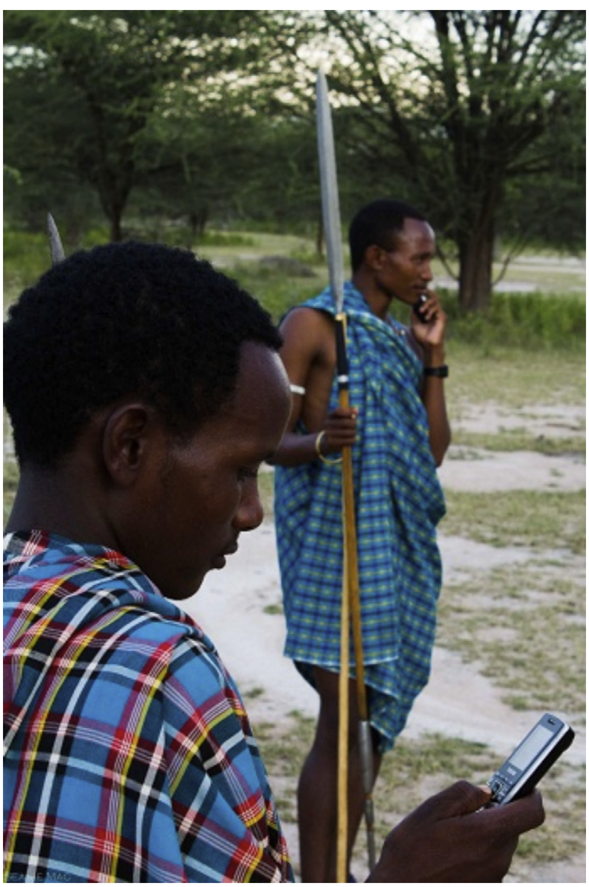

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Figure I. Cell Phones Are Now Widely Used in Rural Areas of Africa. In this case, Barabaig tribesmen discuss the state of their herds. Photo: Amy Dickman.

Combating Poaching

Threatened species fall into two main classes [1]. Some are species with large geographical ranges, but where predatory habitats or large body size makes them locally uncommon within those ranges. The far more numerous have small geographical ranges – a feature that strongly correlates with them being locally uncommon within them. Both sets suffer from habitat loss; poachers persecute the former. These two classes illustrate very different technological challenges.

Preventing poaching in protected areas requires a rapid means to collect, analyze, and report data from the field [31]. Unfortunately, many vulnerable protected areas have a low technical capacity and limited infrastructure. Although a well-trained ranger force and its associated law-enforcement infrastructure is crucial for combating poaching, the increasing sophistication and scale of illegal wildlife trade [32] means that effective conservation requires new tools.

Among the most important data for combating poaching and other wildlife crime are spatial data relayed from the field by law enforcement personnel – rangers – and indeed any locally engaged citizens, whose insider knowledge of their terrain is vital. While numerous options are widely available for analyzing spatial data, these applications require technical skills typically absent at the sites where conservation needs are greatest.

There are conservation database systems for low technical capacity environments. Two early systems were Cybertracker (www.cybertracker.org) and MIST (Management Information System; www.ecostats.com/web/MIST). Cybertracker has been used effectively for ranger-based data collection and monitoring at Kruger National Park, South Africa, and elsewhere [33]. The Uganda Wildlife Authority specifically developed MIST to manage data from protected areas. It has been adopted primarily in sub-Saharan Africa and Asia [34]. Both systems integrate a basic database with GIS and a range of analytical functions, allowing managers to evaluate ranger performance and conduct threat analyses. More recently, a broad consortium of conservation organizations created a bespoke conservation law-enforcement monitoring tool, SMART (Spatial Monitoring and Reporting Tool; www.smartconservationtools.org). A free, open source application, it integrates the ease of field data collection of Cybertracker with powerful analytical and reporting functionality absent from previous solutions. Analysis of data from field staff is largely automated in SMART, allowing field-based users with lower technical capacity to access relevant data, maps, and analysis. Over 140 sites in over 30 different countries now use SMART, with several governments adopting it as the national standard for protected area monitoring.

Other technologies might curtail biodiversity loss through improved protected area management and reduced poaching levels. Drones have potential, but face significant challenges for successful application. They could detect poachers over large landscapes, monitor and follow both animals and people, act as relays for communication in remote areas. They might collect remotely sensed land-cover data at a frequency and resolution not possible or practical with satellite or aircraft-based sensors. However, the drones increasingly used [35] are usually low-cost hobby-grade aircraft with short operating range, basic imaging sensors (typically consumer-grade cameras), and limited ability to transmit data instantly to a ground station. To be effective for anti-poaching efforts and protected area management, conservation drones must approximate military grade capabilities. They should have high-resolution infrared/multispectral sensors, flight times of >5 h, and transmit live imagery to an operator. Conservation systems could employ multiple aircraft in a 'swarm' (e.g., [36]), where centrally controlled aircraft communicate and coordinate with each other to maximize surveillance. At present, drones meeting these specifications are prohibitively expensive for conservation. They require levels of maintenance and repair typically impossible in developing countries.

Both acoustic and metal detectors deployed to the field are under trials (J. Linder unpublished data; D. Morgan, personal communication) as ways to identify phenomena of interest to conservationists (e.g., gunshots, persons carrying firearms). Urban police in the USA already use gunshot detection sensors [37], but their communication and power requirements are presently not easily met in the developing world. Cameras that monitor wildlife also record poachers, and could send these pictures directly to rangers for immediate response [38]. Mobile devices allow rangers and other staff to record rapidly and accurately field data in electronic form, together with GPS data and photographic images. The global proliferation of cellular networks and the rapidly decreasing cost of military-specification ruggedized devices means that some of the most remote and inhospitable environments can collect and rapidly transmit data.

These and other technologies can aid wildlife conservation, but it is important that these tools themselves do not drive conservation efforts. Instead, as military experience shows [39], they should be tactics within a broader conservation strategy. Strengthened legislation and more effective judicial processes are essential, while demand for wildlife products must be curtailed.

Predicting Threat from Changing Land-Use Patterns

Ever more detailed and frequent remote sensing allows detailed assessments of the major driver of species extinction: habitat loss. Improved remote sensing is especially relevant because about two-thirds of all terrestrial species are in tropical moist forests and moreover, a subset of these – the biodiversity hotspots – contain the great majority of threatened species [40]. The challenge is to connect remote sensing with the rapidly expanding data on the distributions of species to anticipate future fronts of species endangerment and then to act accordingly. Conservation applications require this connection to be rapid enough that law enforcement, conservation groups, and others can respond.

Global range maps are available for terrestrial vertebrates, based informally on species distribution records and expert opinion [1]. Studies now permit detailed assessments of the current status of species that trim available range maps with remotely sensed data on elevation and remaining habitats [41] These maps connect directly to meta-population models of the often highly fragmented ranges [42]. New studies show where forest remains outside protected areas, and how it has been lost from within them [43]. There are important limitations.

First, the studies quoted apply to obligate forest species and in places where deforestation creates an obviously unsuitable habitat. Remotely assessing land-use changes to species that live entirely or partly in other habitats requires associating species habitat preferences with the characteristics that satellites measure. This needs to be done directly. Currently, the remote-sensing community classifies habitats into, say, forests or grasslands, while other scientists attempt to match the classified habitats with species' preferences.

Second, species ranges are themselves derived from species locality data. Locality data could be connected directly to remote sensing, a computationally daunting task, but one that would eliminate intermediate steps. Combining crowdsourced data on species distributions anticipates an ability to assess biodiversity continuously and provide a template onto which crowdsourced data could validate predictions of changing species' distributions [1]. Such direct connections could immediately alert managers to where habitat changes are having the most direct impacts on the survival of species.

Inventing the Unexpected: Accelerating the Scale and Speed of Conservation Solutions

The rapid pace of environmental change and biodiversity loss requires developing and evaluating new tools to monitor biodiversity, assess human impacts, and ameliorate them. Challenges, be they the spread of a disease that causes frog extinctions or poaching rhinos for their horn, can emerge very rapidly and demand equally rapid responses. New technologies offer unprecedented abilities to monitor environmental change, create new financial tools, and improve global enforcement against wildlife trade [44]. Existing survey techniques have been slow to use modern technologies such as mobile platforms and big data analytics. Their impact on the species being studied and possible impact on data validity have been inadequately considered. We expect continued improvements and more rapid adoptions. Open source approaches are used by other communities to imagine novel solutions: how might one encourage their use in conservation?

Greater degrees of global connectivity have created new opportunities of Open Source Science that are transforming how scientists make discoveries [45]. We might apply these to conservation. Open source approaches can help develop and/or source new ideas or products, distribute the burden for collecting and analyzing data, and co-design new solutions. They can share in the burdens of research, publication, and funding, while simultaneously engaging the public [46,47].

Open Source Research

Open source or networked science facilitates mass collaboration around science and engineering, particularly for generating non-proprietary new solutions. Open Source Drug Discovery, for instance, created a collaborative platform that harnesses nearly 5000 of the best minds around the world for early-stage research to develop improved, non-proprietary drugs for tuberculosis and malaria [48].

Hackathons

The concept of data software ‘hackathons’ and ‘codefests’ generate novel solutions through collaboration of computer programmers, design experts, and subject experts within an event [49]. Researchers have adapted the concept of hackathons for science and conservation by bringing together interdisciplinary group of scientists, engineers, and technical experts to design new apps, research tools, or identify novel solutions (see e.g., http://conservationhackathon.org).

Prizes and Challenge Competitions

Prizes and challenges crowdsource the world for new solutions, recognizing breakthroughs may not come from expected disciplines or institutions [50]. When problems at the core of a prize or a challenge are well defined, they efficiently focus research and development efforts and capture the imagination of the world's best researchers and innovators. A prize focuses on a single breakthrough, while a challenge helps to create new communities of solutions and practice [51]. Moreover, prizes and challenges lower the costs for new entrants outside of the core discipline of the prize to participate. The Grand Challenges for Development Program at the US Agency for International Development (USAID), in partnership with Gates, Grand Challenges Canada, the Swedish International Development Agency, and others, focused on pressing issues such as the Ebola epidemic, maternal and child health, energy, poverty, and governance and corruption.

New Funding Opportunities

Finally, crowdsourcing has provided new opportunities for not only participating in science, but funding it as well [52]. These platforms include major crowdfunding platforms such as Indiegogo and Kickstarter, but also include smaller, more science-specialized platforms such as Petridish (www.petridish.org), Experiment (www.experiment.com), Microryza (www.microryza.com), and Rockethub (www.rockethub.com). Crowdfunding allows for higher-risk, higher-reward science that overcomes the conservatism of government funding, and forces scientists to build an audience for their work, essential to the public understanding of science.

Concluding Remarks

The rate of technological progress is accelerating. It will almost certainly continue to do so into the future. We confidently expect that technologies for conservation will continue to be better, cheaper, smaller, less invasive, more frequent in the quality of the data they report, and so on. These individual gains, impressive as they are likely to be, nonetheless create problems that we must anticipate. We suggest some of these problems in the Outstanding Questions.

Outstanding Questions

In some conservation contexts, no invasive technology may be permissible. What other non-invasive technologies can we develop to identify species, individuals, and to follow their movements?

How can we make technologies more relevant and accessible to those charged with the practical management of endangered species and ecosystems? How can we feed these data rapidly and coherently to those who make decisions?

How can we broaden outreach to those who collect data on endangered species and ecosystems, and share the results with them? In particular, how do we engage poorly educated, but locally wise individuals with low technical capacity and minimal infrastructure? How can we simultaneously keep these data from those who would use them to do harm?

How can we avoid being swamped with more data than we can analyze and process? How can we filter data to make what we process relevant to key questions?

How can we integrate widely-different datastreams to provide rapid assessments of species and their ecosystems? Examples include combining remote sensing of environments with species distribution data and photographs of species with those who can identify those species. Both technologies are developing rapidly. The challenge is to combine them in ways that allow rapid responses to threats.

How can we adapt technologies to prevent poaching? Poaching often happens in remote places, and those immediately tasked with preventing it may have limited access to technology.

The pace of technological innovation will continue to accelerate, but so too will the problems they must address. How can we best anticipate and, if possible, invent new solutions to conservation problems? How can we imagine technologies that do not yet exist?

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