

A global community-sourced assessment of the state of conservation technology

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Article impact statement: Addressing financing, coordination, and capacity-building constraints is critical to the development and adoption of conservation technology.

Abstract

Conservation technology holds the potential to vastly increase conservationists' ability to understand and address critical environmental challenges, but systemic constraints appear to hamper its development and adoption. Understanding of these constraints and opportunities for advancement remains limited. We conducted a global online survey of 248 conservation technology users and developers to identify perceptions of existing tools' current performance and potential impact, user and developer constraints, and key opportunities for growth. We also conducted focus groups with 45 leading experts to triangulate findings. The technologies with the highest perceived potential were machine learning and computer vision, eDNA and genomics, and networked sensors. A total of 95%, 94%, and 92% respondents, respectively, rated them as very helpful or game changers. The most pressing challenges affecting the field as a whole were competition for limited funding, duplication of efforts, and inadequate capacity building. A total of 76%, 67%, and 55% respondents, respectively, identified these as primary concerns. The key opportunities for growth identified in focus groups were increasing collaboration and information sharing, improving the interoperability of tools, and enhancing capacity for data analyses at scale. Some constraints appeared to disproportionately affect marginalized groups. Respondents in countries with developing economies were more likely to report being constrained by upfront costs, maintenance costs, and development funding ($p = 0.048$, odds ratio [OR] = 2.78; $p = 0.005$, OR = 4.23; $p = 0.024$, OR = 4.26), and female respondents were more likely to report being constrained by development funding and perceived technical skills ($p = 0.027$, OR = 3.98; $p = 0.048$, OR = 2.33). To our knowledge, this is the first attempt to formally capture the perspectives and needs of the global conservation technology community, providing foundational data that can serve as a benchmark to measure progress. We see tremendous potential for this community to further the vision they define, in which collaboration trumps competition; solutions are open, accessible, and interoperable; and user-friendly processing tools empower the rapid translation of data into conservation action.

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KEYWORDS

biodiversity conservation, capacity building, collaboration, funding, global survey, innovation, technology, wildlife monitoring, colaboración, conservación de la biodiversidad, desarrollo de capacidad, encuesta mundial, financiamiento, innovación, monitoreo de fauna, tecnología

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Resumen

La tecnología de conservación tiene el potencial para incrementar considerablemente la habilidad de los conservacionistas para entender y lidiar con los retos ambientales más importantes, pero las restricciones sistémicas parecen dificultar su desarrollo y adopción. La comprensión de estas restricciones y las oportunidades para el avance todavía son limitadas. Encuestamos en línea a 248 usuarios y programadores mundiales de tecnología de conservación para identificar las percepciones existentes del desempeño e impacto potencial de las herramientas actuales, restricciones para los usuarios y programadores y oportunidades clave para el crecimiento. También realizamos grupos de discusión con 45 expertos destacados para triangular los hallazgos. Las tecnologías con el potencial percibido más alto fueron el aprendizaje mecánico y la visión por computadora, la genómica y el eADN y los sensores en red. El 95%, 94% y 92% de los respondientes, respectivamente, clasificó estas tecnologías como muy útiles o como puntos de inflexión. Los retos más apremiantes que afectaron al área como conjunto fueron la competencia por el financiamiento limitado, la duplicación de esfuerzos y el desarrollo inadecuado de capacidades. El 76%, 67% y 55% de los respondientes, respectivamente, identificaron estos retos como de interés primario. Las oportunidades clave para el crecimiento que se identificaron en los grupos de diálogo fueron el incremento de la colaboración y la distribución de información, la mejoría de la operatividad entre herramientas y la potenciación de la capacidad de análisis de datos a escala. Algunas restricciones parecieron afectar desproporcionadamente a grupos marginalizados. Los respondientes de países con economías en desarrollo tuvieron mayor probabilidad de reportar la restricción por los costos iniciales, costos de mantenimiento y la financiación del desarrollo ($p = 0.048$, tasa de probabilidad [OR] = 2.78; $p = 0.005$, OR = 4.23; $p = 0.024$, OR = 4.26), y las mujeres respondientes tuvieron una mayor probabilidad de reportar restricciones por la financiación del desarrollo y habilidades técnicas percibidas ($p = 0.027$, OR = 3.98; $p = 0.048$, OR = 2.33). A nuestro entendimiento, este es el primero intento por capturar formalmente las perspectivas y necesidades de la comunidad mundial de la tecnología de conservación, proporcionando datos fundamentales que pueden servir como referencia para medir el progreso. Vemos un potencial tremendo para que esta comunidad amplíe la visión que definen, en la cual la colaboración se sobrepone a la competencia; las soluciones son abiertas, accesibles e interoperativas; y las herramientas intuitivas de procesamiento capacitan la traducción veloz de datos a acciones de conservación.

INTRODUCTION

Technology has become an essential component of modern biodiversity conservation, enabling more effective data collection, enhanced management decision-making, and targeted monitoring for global and local agreements and goals (Allan et al., 2018; Berger-Tal & Lahoz-Monfort, 2018). These advancements have brought attention to the emerging field of conservation technology, previously defined as the “devices, software platforms, computing resources, algorithms, and biotechnology methods that can cater [to] the needs of the conservation community” (Lahoz-Monfort et al., 2019). We suggest the discipline is further defined by the developers and users of these tools, as well as the market intermediaries that support their engagement. Although no singular technology can solve the current global ecological crisis, devices such as camera traps, acoustic sensors, drones, biologgers, and satellites, as well as increasingly powerful genomic and artificial intelligence applications, hold the potential to empower conservationists to better understand and manage the socioecological systems in which they work.

Recent literature suggests that despite meaningful developments in this discipline, systemic issues such as unsustainable funding and development cycles, inadequate evaluation of solutions, and duplication of efforts are reducing its capacity to keep pace with escalating and emerging conservation challenges (Arts et al., 2015; Berger-Tal & Lahoz-Monfort, 2018; Joppa, 2015). However, understanding of these constraints and opportunities for overcoming them remains limited. It is also uncertain how technologies compare in relative maturity, adoption, and application in conservation settings (e.g., as reflected by Gartner’s technology hype cycle [Blosch & Fenn, 2018]) and how these factors may influence such constraints. These gaps stem in part from the fact that previous researchers focused largely on capturing the progress and limitations of specific technology applications (e.g., Glover-Kapfer et al., 2019; Jiménez López & Mulero-Pázmány, 2019; Kuenzer et al., 2014), rather than the discipline as a whole. Although the few publications that have aimed to capture emerging needs and developments more broadly have provided valuable reviews and expert perspectives (Allan et al., 2018; Pimm et al., 2015; Snaddon et al., 2013), attempts to capture the state of conservation

technology by synthesizing the global community's experiences have not been undertaken. As a result, the most valuable information on the constraints, needs, and opportunities that transcend specific tools still exists primarily in unpublished and dispersed sources, such as virtual events, internal surveys, and online discussion forums for conservation technology users, including those hosted by partnerships such as WILDLABS, SMART, and the Conservation X Labs digital makerspace. Increasing interest and involvement in conservation technology from within and beyond the conservation sector makes it imperative to capture this information now so that future engagement from any stakeholder can be guided by the collective experience of the community thus far.

We examined the global conservation technology community's perspectives and needs through a broadscale online survey of users and developers and focus group discussions with experts. We aimed to understand how existing tools are perceived in terms of current performance and potential capacity to advance the field, key constraints users and developers face, and future directions and primary opportunities for growth in conservation technology. We also explored how reported constraints affecting the development and adoption of conservation technology varied across sociodemographic groups to identify where interventions may be most needed.

METHODS

We surveyed a global community of conservation technology users and developers working across diverse landscapes, conservation challenges, and technologies to address our research questions. We also conducted focus group discussions with leading experts across 7 of the most widely used technology applications in the field to triangulate findings.

This research builds on previous and ongoing efforts to assess user constraints and market opportunities of the global conservation technology sector by WILDLABS—a digital platform and resource hub that catalyzes collaboration to accelerate the development and scaling of technology solutions for conservation impact (www.wildlabs.net). We worked with WILDLABS to harness their unique access to an engaged audience of over 5000 conservation technology practitioners willing to share insights on their experiences. This study was conducted under Colorado State University Institutional Review Board protocol 20–10146H.

Survey design

The survey had 3 sections (Appendix S1). The first focused on respondents' perceptions of the tools they currently use, including the nature of their engagement with conservation technology and which technologies they work with most frequently. Respondents were asked a series of questions about each of the technologies they selected, including their proficiency level and ratings of its overall performance and potential for advancing conservation if current technical challenges were addressed.

They were also asked in an open-ended format about aspects that work well and problems encountered with each technology.

The second section explored respondents' perceptions of the challenges and opportunities facing conservation technology more broadly. We asked respondents to rate the severity of constraints they may face when developing, testing, or using technology for conservation and to rank a series of potential challenges affecting engagement with the discipline. We then asked respondents to indicate their level of optimism about the future of conservation technology relative to 12 months prior and to describe what, if anything, made them feel optimistic. To capture opportunities for the future, we asked open-ended questions about what direction they saw conservation technology going over the next 10–20 years and what they would focus on if they could advance 1 or 2 critical areas in the next 5 years. We compiled options for potential constraints, challenges, and reasons for optimism from open-ended responses to these questions on a WILDLABS community survey from the previous year. We also included an other option for each of these questions.

The third section focused on respondents' sociodemographic information, including questions about their workplace, primary role, and country of residence. Two other sections of the survey were beyond the scope of this article. The survey was designed to take approximately 15 min to complete.

Survey distribution

From July to September 2020, surveys were completed electronically using Qualtrics software. We used nonrandom sampling to reach our target population, including anyone developing, testing, using, or otherwise engaging with technology in a conservation setting and capable of taking an online survey in English. We distributed the survey online through various avenues, including direct emails ($n = 50$), listservs (i.e., WILDLABS community [$n = 3135$], SMART [$n = 500$], Society for Conservation Biology Conservation Technology Working Group open list [$n = 100$]), WILDLABS forum posts, social media posts (i.e., Twitter, Facebook), and 6 conservation technology webinars (average participation = 75 attendees). We also encouraged participants to share the survey with relevant contacts in their networks, employing a virtual snowball sampling method (Baltar & Brunet, 2012).

Survey analyses

Open-ended responses were coded through an iterative thematic process with an inductive content analysis approach (Kynäs, 2020). Initial codes were applied separately by authors T.S. and E.W., then compared and agreed upon mutually. Ultimately, T.S. conducted minor revisions to maximize clarity of comparisons across groups. We report the number of respondents who mentioned each theme to convey relative prevalence (Maxwell, 2010).

To better understand the factors influencing the development and adoption of conservation technologies, we conducted exploratory modeling of variation in the importance of the top 5 constraints reported by users and developers or testers across selected sociodemographic variables. Due to limited sample sizes, we collapsed the scale of constraint ratings into a binary response, combining major and critical ratings to indicate a primary constraint (presence) and ratings less than major to indicate a nonprimary constraint (absence). We selected primary role, national economic development status, and gender as explanatory variables due to their potential influence on access to resources and support for engagement. Economic development status (categorized as developing or developed based on UN classification) was selected rather than country or geographic region due to limited sample sizes outside North America and Europe. We also condensed primary roles into conservationist, technologist, or researcher and excluded the few responses in other categories (e.g., funders or policy makers). Because all respondents identified themselves as either male or female, we used this as a binary variable. The `glm()` function in R allowed us to fit logistic regression models to the binary assignment of responses for each of the top 5 constraints reported by users and developers (see Appendix S5 for model structure and sample sizes). We performed all statistical analyses in the program RStudio (version 1.3.1056) (RStudio Team, 2020).

Focus group design

We conducted 7, 90-min focus group discussions with experts (Bernard, 2017), each on a category of popular conservation technology applications. The focus groups had 4–9 participants (average participation = 6 attendees), plus a moderator and a notetaker, and were conducted via Zoom. The session topics were determined by logically condensing technology groups developed for the survey (described above) and covered camera traps, bioacoustics, biologging, drones and remote sensing, networked sensors and protected area (PA) management tools, environmental DNA (eDNA) and genomics, and machine learning and computer vision. We identified potential participants with a purposive sampling method (Palinkas et al., 2015). We selected subjects from our networks based on their expertise with selected conservation technologies and knowledge of the field, including individuals previously invited to speak at WILD-LABS engagements.

Discussion questions (Appendix S2) were designed to facilitate conversations that would contextualize initial survey findings and illuminate expert opinions by analyzing strengths, weaknesses, opportunities, and constraints (SWOC) within each technology group (Gürel, 2017). Notes on SWOC themes were captured in real time and prioritized through group voting with Miro's online virtual collaboration platform (www.miro.com). We video recorded focus group discussions with participants' informed verbal consent, and T.S. and E.W. transcribed and analyzed them. To protect participant confidentiality, we redacted personally identifying information in the analyses.

Focus group analyses

To analyze focus group transcripts, we used a “key concepts” framework in which we identified factors of central importance to the research questions and captured participant perspectives on these topics (Krueger, 2014). First, high-level thematic codes that captured SWOC themes across groups were developed by analyzing the notes identified and prioritized during focus group discussions. Two coders then read through each transcript in full at least twice, applying these initial codes as appropriate. We prioritized final themes based on the number of applications of each code across focus groups. All focus group analyses were performed with Dedoose software version 8.3.35 (Socio-Cultural Research Consultants, 2020).

RESULTS

Survey respondents

We received 334 survey responses, of which 248 were retained for analyses ($\geq 30\%$ completed), and 161 were fully completed. Respondents in the retained set resided in 37 countries. Most were from the United States ($n = 45$) and the United Kingdom ($n = 26$), followed by India ($n = 10$), Australia ($n = 9$), and Canada ($n = 9$) (Appendix S3). The remaining countries were each represented by fewer than 5 individuals.

Most respondents reported working at conservation non-governmental organizations (NGOs) (37%), universities or research institutions (31%), or technology companies (17%). The remainder worked at private nontechnology institutions (9%), government agencies (4%), or other (1%; e.g., open-source community or retired) (Table 1). Respondents' primary roles at their places of employment were mainly conservation practitioners (32%), technologists (30%), and professors or researchers (22%), followed by students or early career professionals (12%) and other (3%; e.g., investors or policy makers).

When asked about the nature of their engagement with conservation technology, respondents identified themselves most frequently as technology users ($n = 153$), followed by developers ($n = 110$) and testers ($n = 90$) (Table 1). A small portion indicated that none of these options described them ($n = 19$). Over one-half of respondents selected more than 1 form of engagement (57%), and over one-quarter reported participating in all 3 forms of engagement (28%).

Respondents indicated frequently working with a variety of conservation technologies, with camera traps ($n = 112$), GIS and remote sensing ($n = 102$), and machine learning and computer vision ($n = 84$) being the most widely used (Figure 1). The vast majority of respondents reported regular engagement with more than 1 technology group (93%; $n = 214$).

Although sample sizes varied across technology groups, mean proficiency levels were reasonably consistent, ranging from 3.10 to 3.70 (Figure 1). Overall, respondents reported greatest proficiency with PA management tools and GIS and remote sensing; 58% and 53%, respectively, identified

FIGURE 1 Conservation technologies frequently used by survey respondents and mean proficiency scores for each (GIS, geographic information systems; ML, machine learning; UAVs, unmanned aerial vehicles; PA mgmt, protected area management; eDNA, environmental DNA). Respondents reported proficiency levels for each technology they selected on a scale from 1 to 5, with 1 being novice and 5 being expert

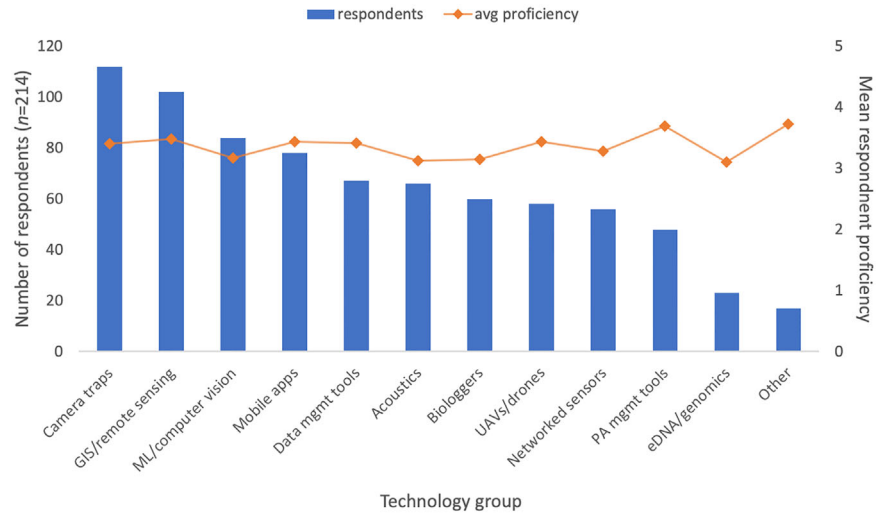


TABLE 1 Summary of sociodemographic characteristics of conservation technology end users and developers responding to a survey on the state of the field

Variable	<i>n</i>	%
Gender		
Male	97	65
Female	52	35
Region		
North America	53	35
Europe	43	28
Asia	25	16
Africa	12	8
Oceania	12	8
Latin America	7	5
Organization type		
Conservation NGO	57	37
University or research institute	48	31
Technology company	26	17
Private (nontechnology) company	14	9
Government agency	6	4
Other	2	1
Primary role		
Conservation practitioner	49	32
Technologist	46	30
Academic or researcher	33	22
Student or early career	19	12
Other	5	3
Technology engagement		
User	153	71
Developer	110	51
Tester	98	46
None	19	9

themselves as being at an advanced or expert level with the technology. Respondents reported lowest proficiency with eDNA and genomics and acoustic devices; 38% and 33% of respondents respectively identified themselves as being at a beginner or novice level with the technology.

Perceptions of current technologies

Survey respondents rated GIS and remote sensing, drones, and mobile apps highest in overall performance; 77% rated GIS and remote sensing as good or very good, and 74% rated both drones and mobile apps as good or very good (Figure 2a). The technology groups with the lowest overall performance ratings were networked sensors, data management tools, and eDNA and genomics: 42%, 46%, and 35% of respondents, respectively, rated them as acceptable and 12%, 6%, and 10%, respectively, rated them as poor or very poor.

In addition to overall performance, survey respondents were asked to rate the technologies’ potential capacity to advance conservation if current problems were addressed. Respondents rated machine learning and computer vision, eDNA and genomics, and networked sensors highest in this category: 95%, 94%, and 92% of respondents, respectively, rated them as very helpful or game changers (Figure 2b). The technology groups with the lowest capacity ratings were mobile apps, data management tools, and camera traps: 20%, 16%, and 13% of respondents, respectively, rated them as nice to have, somewhat helpful, or helpful.

Strengths of current tools

In open-ended survey responses, the leading factors reported to be working well across technology groups included the ecological and management insights that technologies enable (*n* = 100), the increased efficiency and scale of data collection that they facilitate (*n* = 78), and positive aspects of their performance (e.g., speed, range, accuracy; *n* = 72) (Appendix S4). Many

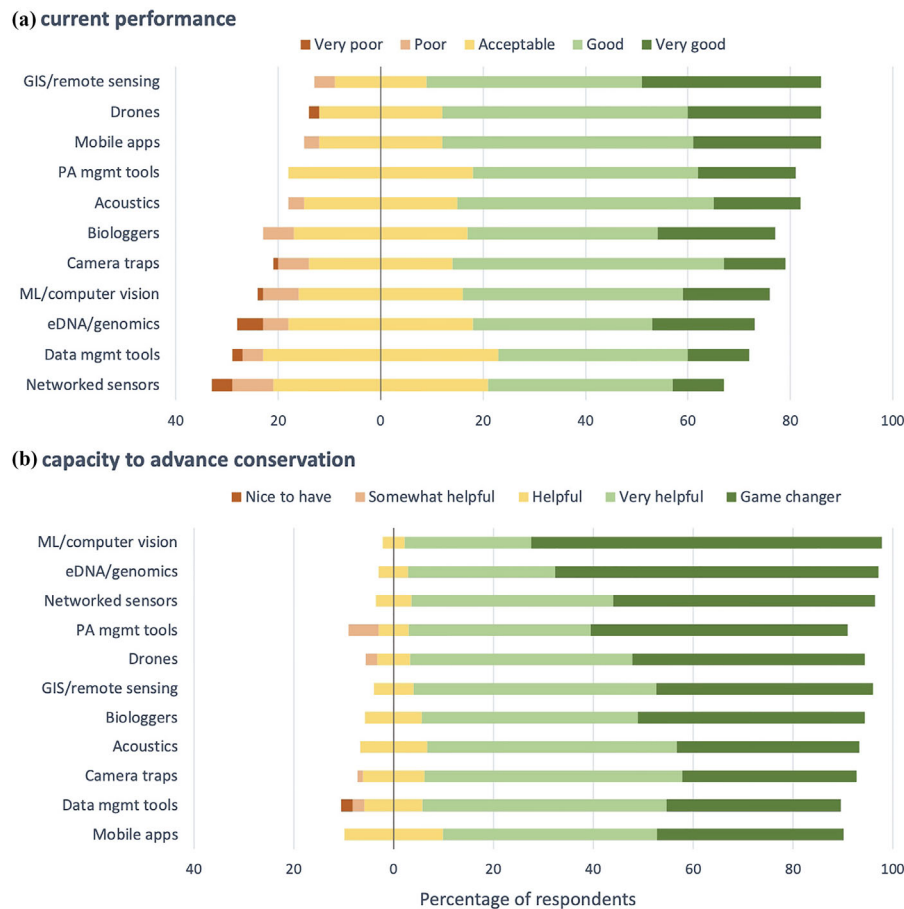


FIGURE 2 Survey respondent ratings of (a) overall performance of conservation technology groups and (b) their capacity to advance conservation if current problems were addressed (abbreviations defined in Figure 1)

respondents also mentioned their accessibility and ease of use ($n = 68$) and the data analytics and reporting they empower ($n = 53$).

Similarly, focus group participants most frequently mentioned ecological insights ($n = 27$), data collection ($n = 20$), and performance ($n = 19$) as strengths of current technologies. In total, 6 of the top 8 focus group strength themes overlapped with those from the survey. The only areas of divergence were that focus group participants did not frequently highlight the increasing availability or versatility of tools and did emphasize the availability of high-quality data (particularly for camera traps, drones and remote sensing, and acoustics; $n = 18$) and benefits associated with the relative maturity of specific technology applications (namely, biologging, camera trapping, and acoustic monitoring; $n = 10$).

Weaknesses of current tools

Many of the themes mentioned most frequently as strengths were also discussed in the context of weaknesses. In survey responses, the most commonly reported issues across technologies related to negative aspects of their performance (e.g., reliability, sensitivity, and accuracy under challenging conditions;

$n = 118$) and accessibility (overall design and support availability, ease of use; $n = 89$) of tools (Appendix S4). Many respondents also mentioned problems with data analytics (particularly the integration and use of machine learning tools; $n = 52$), the cost of technologies ($n = 48$), and power and battery life constraints limiting functionality ($n = 43$).

Focus group participants identified similar current issues, with 5 of the top 8 focus group weakness themes overlapping with the survey. Issues highlighted in the focus groups but not the survey included the quality of some data being collected (e.g., sample quality for eDNA and genomics, training data for machine learning applications, $n = 24$), lack of understanding about and misuse of technologies (e.g., inappropriate expectations of machine learning; $n = 18$), and challenges associated with the relative novelty of specific technologies (e.g., eDNA, edge computing; $n = 9$).

Overarching challenges and constraints

Survey respondents identifying as conservation technology end users reported that their most pressing constraints were costs and technical barriers. They identified upfront costs as the most significant user constraint overall; 62% of respondents rated it

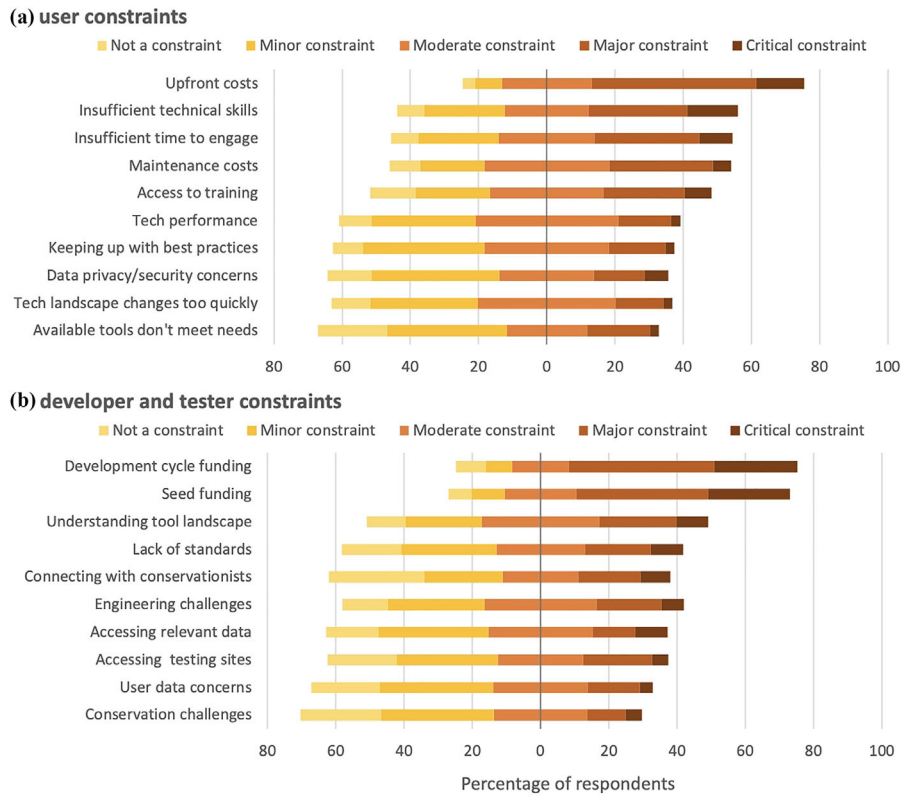


FIGURE 3 Key constraints affecting engagement with conservation technology reported by (a) end users and (b) developers or testers

as a major or critical constraint (Figure 3a). Insufficient technical skills ranked as the next most important user constraint (44%), followed by the time required to engage (e.g., learn new technologies; 41%). Respondents identifying as conservation technology developers and testers reported that financing was also a significant barrier for them. They rated securing funding throughout the development cycle (67%) and securing seed funding for projects (62%) as their top 2 constraints (Figure 3b). Understanding the conservation tool landscape (who is doing what and where the gaps exist) was rated the next most pressing developer constraint (31%).

After removing incomplete entries, we included 106 responses in modeling of user constraints and 92 responses in modeling of developer constraints. The user models indicated that, after adjusting for economic development status and gender, researchers were 3.47 times as likely as conservationists to rate upfront costs as a primary (major or critical) constraint ($p = 0.02$, odds ratio [OR] = 3.47, 95% confidence interval [CI]: 1.25, 10.29), and respondents in developing countries were 2.78 times as likely as those in developed countries to do so ($p = 0.048$, OR = 2.78, 95% CI: 1.04, 7.99) (Appendix S5). Similarly, respondents in developing countries were 4.23 times as likely as those in developed countries to rate maintenance costs as a primary constraint ($p = 0.005$, OR = 4.23, 95% CI: 1.59, 12.06). Finally, female respondents were 2.33 times as likely as male respondents to rate technical skills as a primary constraint ($p = 0.048$, OR = 2.33, 95% CI: 1.01, 5.49). Model results for

these variables were not statistically significant for user constraints regarding the time required to engage or training access.

For developer constraints, respondents in developing countries were 4.26 times as likely as those in developed countries to report securing funding throughout the development cycle as a primary constraint when adjusting for variability in role and gender ($p = 0.024$, OR = 4.26, 95% CI: 1.32, 17.09), and female respondents were 3.98 times as likely to do so as their male colleagues ($p = 0.027$, OR = 3.98, 95% CI: 1.27, 15.42). Technologists were also 3.65 times as likely as conservationists to report connecting with conservation technology end users as a primary constraint ($p = 0.041$, OR = 3.65, 95% CI: 1.12, 13.95). Model results were not significant for any of the other 3 top developer constraints.

Regarding challenges facing the field of conservation technology overall, survey respondents ranked competition for limited funding (mean = 2.99), duplication of efforts (mean = 3.64), and technology adoption and capacity building (mean = 4.31) highest; 76%, 67%, and 55% of respondents, respectively, ranked them in their top 4 (Figure 4). Failing to live up to hype (mean = 4.69; 34%), confusion in the market (mean = 5.35; 18%), and overlooking ethical problems (mean = 6.47; 13%) were the lowest ranking challenges overall.

Experts in the focus groups, in contrast, most frequently underscored constraints relating to external barriers (e.g., regulations, permitting, governance, local capacity; $n = 39$) and insufficient understanding and evaluation of technology impact

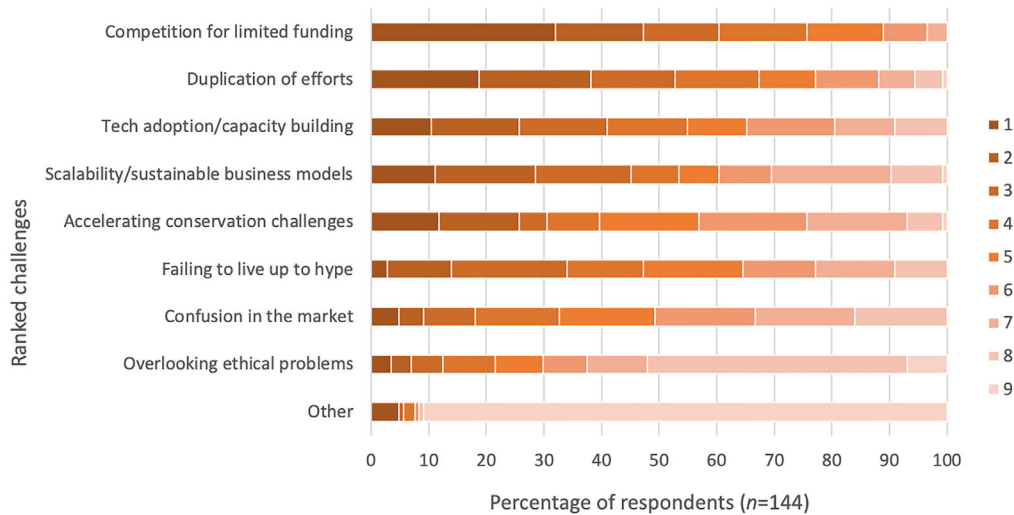


FIGURE 4 Survey respondent rankings of the greatest challenges facing the field of conservation technology (1, most important; 9, least important)

(e.g., unforeseen consequences of technologies on wildlife and communities, influence on conservation policy; $n = 27$). Many participants also mentioned challenges related to securing sustainable funding ($n = 27$), engaging a commercial market (e.g., sustainable business models, limited demand for bespoke conservation tools, the dominance of select few developers; $n = 23$), and the usability of tools ($n = 23$). The lack of standards (for data, methods, best practices; $n = 20$) and challenges of effective collaboration and information sharing ($n = 20$) were also mentioned frequently.

Opportunities for growth

Despite these challenges, more than half of survey respondents (52%) reported feeling more optimistic about the future of conservation technology relative to 12 months prior. Only 7% reported feeling less optimistic, and 41% reported feeling about the same. When asked to rank potential reasons for optimism from 1 to 7, with 1 being most important, respondents indicated that the increasing accessibility of conservation technologies (mean = 2.5) and the rate at which the field is evolving (mean = 3.0) were most important: 76% and 61%, respectively, ranked them in their top 3. The culture of collaboration (mean = 3.3; 54%) and growing support from the conservation community and decision makers (mean = 3.5; 47%) were the next most important factors.

In open-ended responses about conservation technology developments in the coming years, most survey respondents emphasized leveraging machine learning and computer vision for improved data analytics ($n = 68$), followed by increasing data collection efficiency and scale ($n = 49$). More effectively translating data into useful management information ($n = 39$), improving hardware design and performance ($n = 38$), and better-integrating tools and data streams ($n = 35$) were also top priorities for survey respondents.

Participants across all 7 focus groups reinforced many of these themes when asked to identify opportunities for growth, most frequently highlighting increasing collaboration and information sharing ($n = 43$), improving the interoperability of tools and data streams ($n = 32$), and enhancing capacity for meaningful data analyses at scale ($n = 30$) (Table 2). One of the most explicit calls for action across 6 of the 7 focus groups was improving data sharing ($n = 25$) with particular emphasis from participants working with biologists and acoustics on establishing open data repositories to facilitate the storage, curation, and analysis of global data sets. Under the umbrella code of collaboration and information sharing, respondents saw an opportunity for a convening body, established following a national lab model, that with sufficient funding could facilitate the level of global collaboration and coordination needed to capitalize on the suggestions above. Opportunities to increase the efficiency and scale of data collection ($n = 24$), invest in local capacity building ($n = 20$), and improve the accessibility of tools ($n = 19$) were also mentioned frequently.

DISCUSSION

Catalyzed by dramatic declines in biodiversity, calls to increase the use of technology in conservation are common. However, strategic targeting of technology development efforts and user support will amplify their positive impacts. Our results highlight how conservation technology is perceived by engaged users and developers, identifying key insights on current performance, systemic challenges, and opportunities for growth. Our global analysis of the state of conservation technology showed that perceptions varied across technologies regarding current performance and potential capacity to advance the field (machine learning and computer vision, eDNA and genomics, and networked sensors were viewed as areas with highest untapped

TABLE 2 Most frequently mentioned opportunities for advancing the field of conservation technology identified by participants across 7 technology-specific focus group discussions

Theme	Definition	Total mentions	Occurrence across focus groups (%)
Collaboration & information sharing	Improving how actors in the field work together	43	100
Interoperability	Improving how tools and data streams can be used in concert	32	100
Data analysis	Expanding capacity for analysis of data being collected	30	100
Bespoke tools	Developing fit-for-purpose conservation technologies	28	86
Data sharing	Increasing capacity to share, store, and collate data globally	25	86
Data collection	Increasing capacity to collect data more efficiently and at larger scales	24	86
Local capacity building	Investing in technical capacity and training of local partners	20	86
Ease of use	Making tools more accessible and user friendly	19	100

potential); the most pressing constraints affecting conservation technology development and adoption were unsustainable financing, lack of coordination of efforts across domain boundaries, and inadequate capacity building (notably, some constraints appeared to disproportionately affect female respondents and individuals in developing countries); and the primary opportunities for growth included increasing collaboration and information sharing across projects, improving interoperability of tools and data streams, and enhancing capacity for data analyses at scale.

Performance and relative potential of current tools

Many of the benefits and shortfalls of current conservation technologies already reported for individual tools held true across applications in our research. Overall, conservation technologies were consistently reported to improve the efficiency, scale, and quality of data collection, enable new and more frequent ecological and management insights, and empower conservationists to ask more useful and interesting questions of these data with increasingly powerful analytics and reporting tools (Berger-Wolf et al., 2017; Kays et al., 2015; Wall et al., 2014). However, recurring problems were also reported to be hampering the utility of conservation technologies in practice, including their reliability and performance in challenging conditions, limited power and data storage capacities, reliance on landscape connectivity for data transmission, and accessibility to conservation end users (Jiménez López & Mulero-Pázmány, 2019; Newey et al., 2015).

Assessing survey respondent ratings of each technology group's current overall performance compared with their capacity to advance conservation if issues were addressed revealed perceptions of these tools' potential trajectories. The 3 most highly rated technologies regarding capacity to advance con-

servation (machine learning and computer vision, eDNA and genomics, and networked sensors) were all rated comparatively low on current performance. This finding suggests these technologies are viewed as having substantial room for and likelihood of further development, making them areas worth exploring for investment. Other technology groups appeared to be seen as either already meeting their potential, as indicated by high current performance and low or moderate capacity ratings (e.g., mobile apps, GIS and remote sensing, and drones), or as having room for improvement but less likelihood of influence on the field based on these upgrades, as indicated by comparatively low ratings on both fronts (e.g., data management tools and camera traps).

This variation in perceived potential may be partly attributed to each technology's relative novelty to conservation or where they fall on the Gartner technology hype cycle (Blosch & Fenn, 2018). Newer tools such as eDNA or machine learning may be more likely to be rated as potential game changers, aligning with Gartner's peak of inflated expectations. In contrast, tools with more established conservation applications, such as camera traps, could be perceived as having already revolutionized the field, therefore having progressed to a plateau of productivity. Some applications may be underestimated in their remaining potential; for example, the emergence of widely available next-generation camera traps (Glover-Kapfer et al., 2019) and smartphone apps that support artificial intelligence models (e.g., Edge Impulse applications) (Kelling, 2018) may shift perceptions of these tools. Continued research on ratings of these technologies' relative performance and potential influence would be helpful for understanding trends in perceived value over time. Although we had a relatively even distribution of expertise across technologies, sample sizes were limited for some applications, including eDNA and genomics, PA management tools, and networked sensors. Because survey respondents were heavily concentrated in countries with developed economies, the technologies represented likely also most accurately reflect the

context of this demographic. Future research should strive to reach a more diverse base of respondents to gain further insight into the perceptions of these currently underrepresented end user communities.

Critical constraints

Despite upward trends in spending on biodiversity (Seidl et al., 2020) and the increasing availability of low-cost, open-source tools (e.g., Hill et al., 2018), our results indicate that sustainable financing remains a primary constraint to effective engagement with conservation technology by both developers and end users. Although insufficient funding is a pervasive and frequently discussed constraint across the conservation sector, the growing involvement of corporate technology companies in conservation technology (e.g., Microsoft, Google, Arm) can shift financing dynamics substantially in this context. Our data showed that currently developers still struggle with the dual challenges of securing seed funding and continued financial support throughout the development cycle, the latter of which was previously identified as a significant barrier to the scaling and sustainability of bespoke open-source applications (Hill et al., 2019). Beyond direct financial support, focus groups underscored a lack of sustainable business models and corresponding markets as limitations on bespoke conservation technologies' success, which have also been discussed previously (Iacona et al., 2019; Lahoz-Monfort et al., 2019). End users also face challenges of covering upfront costs, recently identified as the top constraint reported by a global community of camera trap users (Glover-Kapfer et al., 2019), and ongoing and unexpected maintenance costs. The fact that competition for limited funding was ranked highest by survey respondents in overall challenges facing the conservation technology field highlights how closely tied financial concerns are to the second highest priority constraint—coordination of efforts.

The current general approach of conservation technology efforts has been described as a “patchwork of one-off projects and partnerships” which “wastes time, money, and resources in a discipline that can ill-afford to do so” (Joppa, 2015). Additionally, emphasis on technology hype and good news narratives over rigorous evaluation has allowed for incomplete development processes or the rapid development of these one-off solutions without ensuring their effectiveness, scalability, or long-term sustainability (Arts et al., 2015). Our results reinforce these observations, with duplication of efforts ranked as the second most important overall challenge facing the field of conservation technology and lack of standards and understanding the tool landscape both within the top 5 reported developer constraints.

A recent call for action contended that overcoming these issues and harnessing conservation technology's potential would require an internationally coordinated leadership strategy to develop and nurture a functional organizational system (Lahoz-Monfort et al., 2019). However, the urgent need for innovative funding mechanisms to accommodate this type of multidisciplinary innovation and scaling of efforts was iden-

tified over a decade ago (Benson et al., 2010) and remains pertinent today. Existing organizing bodies such as the International Biologging Society and the Society for Conservation Biology (SCB) Conservation Technology Working Group act as conveners but are limited in their capacity to facilitate strategic coordination because this in itself requires sustained resources. As it is, many of the highest impact collaborative efforts are mobilized around a single technology solution and often financially backed by a corporate technology partner (e.g., Wildlife Insights, SMART, EarthRanger). Although these initiatives can and should lead by example in ensuring effective collaboration around and interoperability of their tools, relying on them to provide strategic coordination for the broader sector is problematic for several reasons, including that this is largely beyond their capacity and would likely be influenced by internal agendas that necessarily prioritize the success of their tools. Many of these efforts also still face significant challenges scaling to reach their own full potential, demonstrating that the time, resources, and ability to negotiate the trade-offs required to achieve common solutions remain difficult for even the most successful initiatives.

The third highest priority constraint we identified was inadequate capacity building, with technology adoption and capacity building ranked third in overall challenges and both skill barriers and training access making the top 5 user constraints, all of which were reinforced in expert focus group discussions. Exploratory modeling of constraints across sociodemographic groups revealed that some issues might disproportionately affect marginalized user and developer communities. Respondents in countries with developing economies were more likely to report being significantly constrained by both upfront costs and maintenance costs than those in developed countries, and female respondents were more likely to report being constrained by technical skills than male respondents. Both female developers and those in developing countries were also more likely to report struggling to secure funding throughout the technology development cycle. These trends reflect broader societal dynamics at work in both the conservation and technology sectors (Jones & Solomon, 2019; Varma, 2018).

Large discrepancies exist in support for engagement in conservation between low- and high-income countries, ranging from research outputs and ownership to national spending, despite generally higher biodiversity and increased impacts of climate change in developing countries (Fazey et al., 2005; McClanahan & Rankin, 2016; Shukla et al., 2019). Previous literature shows that in light of these discrepancies, prioritizing capacity building and engagement with local communities in conservation technology efforts holds tremendous potential for integrating local and traditional ecological knowledge and ensuring the long-term sustainability and effectiveness of solutions (Anadón et al., 2009; Berkes, 2004; Pimm et al., 2015). This literature also suggests that failure to do so can undermine conservation efforts and contribute to the marginalization of local and Indigenous communities (Duffy et al., 2019; Shrestha & Lapeyre, 2018).

Similarly, mounting evidence of the influence of gender inequality in conservation, ranging from the inextricable link

between gender-based violence and environmental degradation to the conflict of roles many women in the field face between motherhood and leadership, has led to recognition that promoting gender equality is essential to advancing conservation (Agarwal, 2009; Castañeda Carney et al., 2020; Jones et al., 2020). Although gaps in self-perception may partially explain the differences identified here between male and female respondents in reported technical skills (Hargittai & Shafer, 2006), more investigation is needed to understand their implications, particularly concerning intersectionality in the field of conservation technology. Our survey also targeted users already engaging in the sector, therefore reflecting existing biases in participation. It is possible that differences across sociodemographic groups would be altered in a survey with broader reach. Acknowledging that these issues are likely compounded in the context of technology by the digital divide, furthering existing inequalities regarding access to basic digital engagement, it is clear that efforts to evaluate and address potential social exclusion will be fundamental moving forward.

Although overlooking ethical concerns was ranked lowest by survey respondents in overall challenges facing the field, insufficient evaluation of the impact was a top constraint across all 7 focus group discussions, suggesting that this may be a higher level concern considered more frequently by experts than the average user or developer. Previous literature also indicates this is an area of increasing importance to the discipline, raising concerns that, if implemented inappropriately, conservation technologies may reinforce historical injustices and further separate conservation data and decision-making from those most affected by them (Adams, 2019; Bryant, 2002). Although awareness of these issues is not yet widespread, experts are working to illuminate and address them. For example, trepidations about the social risks of tools such as drones and camera traps being deployed without appropriate legislative and ethical frameworks (Humble et al., 2014; Sandbrook et al., 2018; Wallace et al., 2018) recently led to the development of guidelines for the socially responsible use of surveillance technologies (Sandbrook et al., 2021) and an ethical code of conduct for camera traps in wildlife research (Sharma et al., 2020). The first formal guidance on addressing data privacy concerns when using social media data in conservation science was also recently published (Di Minin et al., 2021).

Although our results provide insight into the top constraints inhibiting effective development and adoption of conservation technology, more research is needed to understand how to overcome these barriers most effectively. Limited sample sizes from regions beyond North America and Europe restricted our ability to look into differences in constraints across geographies or how they might interact with other variables. Making future surveys available in languages other than English would make these analyses more feasible. Similarly, unequal distribution of respondents across technology groups limited our capacity to assess how constraints varied based on the tools being used. However, our data provided a solid foundation of community-sourced feedback demonstrating that sustainable financing, coordination, and capacity building should be top priorities for investment and call attention to the need for critical, intersectional

assessments of how gender dynamics and national economy may affect engagement.

Opportunities and future directions

Feedback from the global conservation technology community of practice describes an ideal vision of this emerging field 10–20 years from now in which collaboration trumps competition; solutions are open, accessible, and interoperable; and user-friendly data processing and management tools empower the rapid translation of data insights to conservation action. Recent years have already seen significant advancements in collaborative efforts, as evidenced by the culture of collaboration ranking third in reasons for optimism by survey respondents. Increasingly, innovative partnerships lead the way in demonstrating the power of cross-sector collaboration to deliver solutions at scales that would otherwise be unfeasible. Although willingness to collaborate and share information appears to be growing, the infrastructure to support broader engagement in these activities is still mostly lacking. For this reason, establishing open, community-curated data repositories was one of the most frequently identified opportunities in focus groups, particularly by acoustics and biologging experts who do not currently reap the benefits of tools such as Wildlife Insights. Previous calls have been made for similar infrastructure to accommodate global, multiyear acoustic data sets (Gibb et al., 2019). Notably, community science platforms (e.g., Zooniverse) have massively advanced public engagement with conservation-data processing but have been similarly dominated by camera trap imagery. According to focus group participants, lack of resources and agreed-on data standards have thus far impeded progress, highlighting the need for targeted investment in such infrastructure to support collaboration among willing actors. Establishing a sustainably funded convening body for conservation technology, the other most frequently identified opportunity for facilitating collaboration, could play a critical role in both resourcing and defining industry standards. Descriptions of a convening body echoed recent calls for international leadership to realize the field's potential (Lahoz-Monfort et al., 2019). Still, much work is needed to identify a realistic path forward in making this vision a reality.

The second most frequently identified opportunity for advancement was improving the interoperability of conservation technologies. Reinforcing predictions in previous literature (e.g., Marvin et al., 2016), focus group participants articulated that we are moving beyond one-off applications into the phase of next-generation ecological monitoring, defined by integrated and accessible multimodal data streams. Widespread commitment to delivering low-cost, open-source solutions and empowering collaboration across existing platforms will be fundamental to realizing this vision, which holds the potential to overcome many of the current challenges identified by end users. A critical component of increasing interoperability is understanding what, and who, already exists in the space. To meet this need, WILDLABS and collaborators are currently building infrastructure to host an interactive global conservation technology network directory but will require

broad engagement from users to maintain it as the sector evolves.

As environmental sensors of all kinds become cheaper, better, and more easily integrated, conservationists' need for accessible and effective data processing and analysis tools is increasingly apparent (Benson et al., 2010). Machine learning and computer vision applications have thus far focused mainly on improving the accuracy of models and processing pipelines for camera trap data (e.g., Beery et al., 2019; Norouzzadeh et al., 2018), but applications in other realms such as bioacoustics are rapidly developing (Stowell et al., 2019) and are predicted to have dramatic impacts on biodiversity monitoring in coming years (Kelling, 2018). However, as demonstrated in the reported weaknesses of machine learning and computer vision (Appendix S4), many artificial intelligence tools remain inaccessible to conservationists due to the technical skills and costly computing resources they require. Although user-friendly platforms (e.g., Wildlife Insights, Microsoft's MegaDetector) are significant improvements, more initiatives dedicated to supporting under resourced individuals with funding and industry-expert mentorship (e.g., WILDLABS' new fellowship program) are needed to overcome barriers and deliver sustained impact. Such efforts will also play a critical role in catalyzing opportunities for cross-disciplinary work and matchmaking between the conservation and technology sectors.

To our knowledge, this is the first attempt to formally capture the perspectives and needs of the global conservation technology community. Although many of the systemic challenges we identified may be known to those already immersed in the discipline, this research provides foundational data on the current state of perceptions that can serve as a benchmark to measure progress. Continued research at regular intervals and in varied contexts will be necessary to understand how conservation technology needs and applications develop with evolving conservation challenges and the dynamic commercial technology sector. More immediately, we hope that readers using and developing conservation technologies recognize the tremendous capacity of this community to drive the field forward with a united voice and that those with much-needed resources and expertise seize the opportunity to support them.

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