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Local conservation action requires ethical investments in global digital equity

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Summary

Satellite remote sensing is vital for monitoring anthropogenic changes and for alerting us to escalating environmental threats. With recent technological advances, a variety of satellite-based monitoring systems are available to aid conservation practitioners. Yet, documented knowledge of who uses near-real-time satellite-based monitoring and how these technologies are applied to inform conservation decisions is sparse. Through an online survey and semi-structured interviews, we explored how developers and users leverage conservation early-warning and alert systems (CEASs) for enhanced conservation decisions. Some 167 developers and users of near-real-time fire and forest monitoring systems from 40 countries participated in this study. Globally, respondents used 66 unique CEASs. The most common applications were for education and awareness, fire/disaster management and law enforcement. Respondents primarily used CEASs to enforce land-use policies and deter illegal activities, and they perceived these tools as underutilized for incentivizing policy compliance or conservation. Respondents experienced inequities regarding system access, exposure and ability to act upon alert information. More investments in capacity-building, resources and action plans are needed to better link information to action. Implementing recommendations from this research can help us to increase the accessibility and inclusivity of CEAS applications to unlock their powerful capabilities for achieving conservation goals.

Introduction

Satellite remote sensing is an integral tool to help monitor environmental changes and alert us to emerging environmental threats in close to real time (Tabor & Hewson 2018). Conservation practitioners utilize various digital technologies and data platforms to collect and disseminate data for conservation applications (Palomino et al. 2017, Lahoz-Monfort & Magrath 2021, Speaker et al. 2022). This research investigates the current state of a subset of conservation technology called conservation early-warning and alert systems (CEASs) and their applications (Tabor & Holland 2021). CEASs monitor or forecast ecosystem changes and alert land managers and decision-makers to emerging threats. There is now an abundance of geospatial datasets, data platforms and application programming interfaces available to aid conservation practitioners (Palomino et al. 2017, Tabor & Hewson 2018), including dozens of fire and forest monitoring tools (Tabor & Holland 2021). Advances in technology have helped increase access to satellite-based monitoring (SBM) by alleviating local computing restrictions, financial constraints and expertise barriers required to use Geographic Information System (GIS) technologies (Tabor & Hewson 2018). However, there is scarce published literature documenting how CEASs aid conservation decisions with measurable outcomes and where they fall short.

Based on the demonstrated use of early-warning and alert systems for humanitarian applications, CEAS applications can help improve decision-making to mitigate ecosystem degradation. Early-warning and alert systems for climate services, food security and disaster risk-reduction applications provide a rich history to inform the development of CEASs, given the nascent nature of the field. For example, we know from humanitarian applications that often key decision-makers experience barriers to accessing or using the alert information. These barriers range from the political environment, lack of trust in the information, ineffective communications or a lack of resources (Tabor & Holland 2021).

In accordance with humanitarian early-warning and alert systems, the sparse literature published on CEASs resonates with common reasons why conservation practitioners underutilize digital technologies. Barriers to use of the tools often stem from inadequate infrastructure, poor technology design, insufficient resources, lack of authority or distrust in systems/data (Davies et al. 2009, Jepson & Ladle 2015, Finer et al. 2018, Musinsky et al. 2018, Weisse et al. 2019, Shea 2022). However, these studies focused on single tools and disproportionately represented specific user groups (e.g., government personnel in Latin America). There is a gap in understanding the barriers to the broader suite of CEASs, as experienced by users representing diverse roles and demographics. Understanding these barriers is crucial, as unequal access to technologies can amplify social and economic inequities

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and further marginalize communities (Elwood 2008). This begs the question: what are the most common enabling conditions influencing the utility of CEASs that demonstrate the ability to effect favourable change in conservation outcomes? With this research, we present the barriers to the access and use of CEASs identified by a diversity of technicians and decision-makers, and we assess how technology design and unequal access to digital technologies affect CEAS applications. Adopting a mixed-methods approach, we inventoried the conservation applications of CEASs accessed by users globally, and we examined how these barriers perpetuate inequity across different user groups. Using a human-centred approach to understand the user needs and cultural contexts tied to tool users by different groups (Knight et al. 2019), we sourced recommendations from users and developers to help improve systems and enable informed conservation actions. This is the first comprehensive study of CEASs that describes who uses these systems and how they see the relevance of the alerts to their conservation actions/decisions. This research can inform improved system design, operation and engagement with diverse users to unlock the powerful capabilities of CEASs to achieve conservation objectives.

Methods

We used semi-structured interviews and online surveys with both users and developers of CEASs to document the applications and barriers experienced by different users. We also investigated the opportunities and risks of using surveillance technologies and sourced recommendations for improving CEASs.

Sampling design and data collection

First, we identified a sample of CEAS developers with some representation from each major region across the global tropics, intending to conduct virtual interviews with equal representation of CEAS developers who manage systems at different scales. We defined developers as the people who created or supported the design and development of systems and actively managed the systems. We included developers whose systems provided monitoring and alerts in multiple regions in the global tropics and those who managed systems that operated at a global, continental, national or subnational scale. This process stratified the sample to increase the representation of diverse user groups and scales of CEASs. We then used snowball sampling for additional interviews (Goodman 1961) by asking the developers we interviewed to connect us with users of their systems for additional interviews. We ensured that any communications with users complied with the privacy agreements between the systems and the users.

Following the interviews, we distributed an online survey by asking the interviewees to distribute the survey through their networks, including their system subscribers located in the Global South. To cast a broader net, we disseminated the online survey through various global listservs to reach current and potential users of CEASs, including the Society for Conservation GIS, the Global Forest Observation Initiative and the Conservation Remote Sensing Network. The online surveys were available in English, Spanish, French, Portuguese and Bahasa Indonesia.

Research ethics and data management

We submitted all research materials as a protocol to the University of Maryland, Baltimore County's Institutional Review Board and received approval for exempt research (protocol code #561). We removed personal identifiers from the interview transcripts, and survey responses were anonymized.

Interview strategy and online survey

We generated two sets of guiding interview questions uniquely for developers and users of CEAS using a constructionist approach allowing the follow-up questions to take shape based on the responses from the interviewee (Appendix S1). We asked open-ended questions so as not to lead the interviewees towards answers that might reinforce preconceptions held by the interviewer (Malterud 2001). This also allowed the interview to follow the set of experiences and narrative arc that the interviewee most wanted to share rather than redirecting the interviewee to secure a response to all questions. This more inclusive and adaptive format diversified and enriched the resulting set of user stories. The developers we interviewed already knew the interviewer and therefore knew of their experience as a CEAS developer. We never explicitly told the users who we interviewed of our experience, and we had no knowledge of their awareness. Therefore, through self-awareness and reflection during the interview process, we tried to mitigate potential power imbalances between members of our research team, who held experience as technology providers, and the user, with possibly less access to and ownership of the technology. We intentionally aimed for a more inclusive interview process with this approach.

The topics of the interview questions for CEAS users aimed to collect the following data: how users currently use CEASs; barriers to effective CEAS use; and recommendations for overcoming obstacles to use and improving tool design. For the CEAS developers, we asked them to answer the application questions regarding how they believe or know, through previous evaluations, how users apply their tools. We recorded the full interviews with participant consent and transcribed them using Temi's online transcription service (Temi 2022).

The responses to the interview questions shaped the questions we asked in the online survey (Appendix S2). We designed the online survey questions to stratify the barriers to systems incurred by different types of developers, users, applications and geographies.

Data analysis

We coded the transcription data using *Dedoose* version 9.0.54 (Dedoose 2022) to capture both recurring themes and outliers in the responses. We used qualitative content analysis to summarize the thematic information produced from the interviews (Sandelowski 2000). Specifically, we categorized types of users, applications, barriers to tool use and recommendations for overcoming barriers. We compared the applications and barriers identified in the coded analysis with those in the literature and examined how the barriers were different or the same for distinct user groups.

Applying 'human-centred design' (HCD) aims to increase technology adoption by building a tool to meet user needs and by pulling together methods from diverse disciplines (e.g., engineering, anthropology, psychology and design) to inform application (Brenner et al. 2016). Borrowing from HCD, we used the approach of developing 'user stories' to translate the developers' and users' application stories from a long narrative into a concise statement. Developers use 'user stories' to describe an application while capturing a user's requirements and perceived values of technology

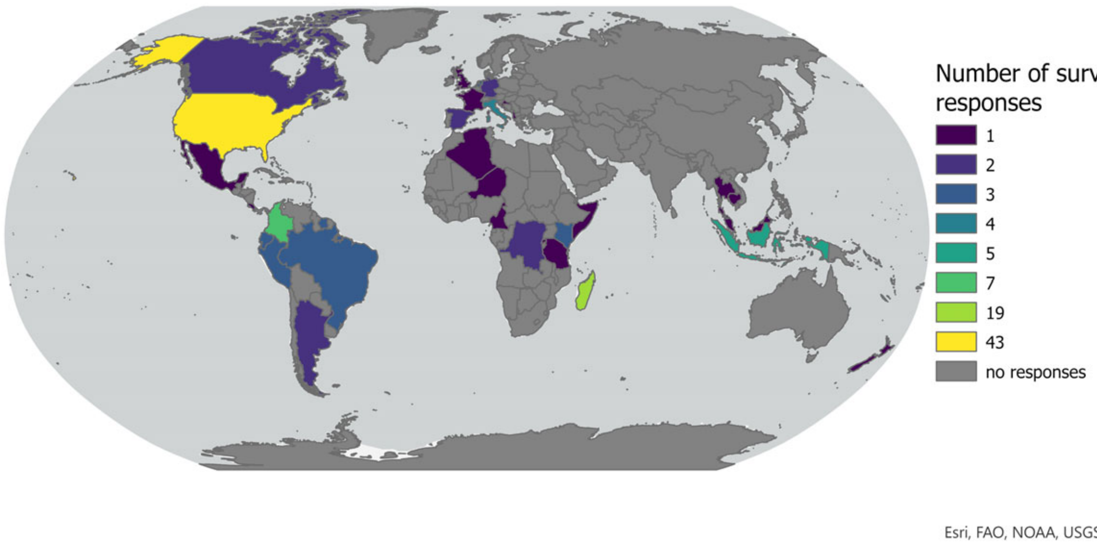

Figure 1. Numbers of respondents to the online survey.

in achieving a specific outcome (Cohn 2004). The statement model was: who (role) did what (action) and why (for what benefit)?

We used *Qualtrics* survey software (Qualtrics 2022) to create and manage responses to the online survey, which was open for 2 months, from mid-February to mid-April 2022. We collected and translated all written responses into English before using qualitative content analysis to code responses by category. Some answers fell into multiple categories and were assigned more than one code. We highlighted repeated themes and noted responses that were unique or represented less common ideas but also represented diverse perspectives on innovative ideas. Finally, we compiled free-form responses from survey respondents and coded interview data to annotate the quantitative survey data.

Results

Some 167 developers and users of near-real-time (NRT) fire and forest monitoring systems from 40 countries participated in this study by sharing their insights and experiences through virtual interviews and an online survey. Collectively, these participants provided a global perspective with rich insights into CEAS applications, limitations and possible future directions. From these results, we made recommendations to help users leverage CEASs for more significant conservation outcomes.

Survey and interview participation

We interviewed 13 developers of CEAS systems, including five global system developers and eight regional/national/subnational system developers based in the following continents (with numbers in parentheses): North America (4), Europe (2), South America (4), Australia (1), Africa (1), and Asia (1). We contacted at least one user of each system from the developers' suggestions, but only four users in total agreed to an interview. Unfortunately, language barriers and reliable internet access to participate in virtual interviews limited the study sample for users. The four users who we did interview were from Sri Lanka, Brazil, Australia and Niger.

The online survey provided more perspectives from developers and users. Some 150 people from 38 countries participated in the online survey (Fig. 1). The breakdown of users by system scale indicated a representative sample of systems. Forty-two respondents indicated they used global systems, 72 used regional systems and 31 used national or subnational systems. Respondents represented a diversity of roles related to their use of systems. Some 30% of respondents identified as 'researchers', 28% as 'users', 19% as 'product/system developers', 13% as 'advocates', 8% as 'trainers/educators' and 3% as 'other'.

Close to two-thirds of respondents self-identified as men, with 34% identifying as women and 3% preferring not to answer. While close to 50% of the respondents self-identified as being of either 'European' or 'Hispanic/Latinx' descent, respondents also represented 'African', 'Asian', 'mixed race' and 'persons of Indigenous descent'.

Systems and applications

Respondents reported using or developing 66 unique systems for diverse applications (Table 1). Although not prompted, some respondents named 11 satellite instruments instead of systems: MODIS, Sentinel, Landsat, VIIRS, AVHRR, SPOT, GOES, Sentinel-2, WildfireSat, EUMETSAT and Planet.

In addition to the variety of systems used, the interview and survey data indicated that users were collating information from multiple systems and data sources to inform decision-making. NRT fire hotspot information from polar-orbiting and geostationary satellites (i.e., MODIS, VIIRS, NOAA) is redundant across multiple platforms, yet users indicated leveraging all systems available to them. Users stated the risk of dependence on single systems because they had no control over whether the system discontinued operation. Furthermore, using multiple systems was an information backup strategy because operational systems could experience downtimes. Some 58% of users indicated that they used more than one system and data source for monitoring, and 35% indicated using more than three systems. Through the interviews we learned that users leveraged multiple systems to reduce data gaps and verify alert accuracy. For example, SBM with optical sensors can miss forest disturbances and fires due to clouds obscuring observation or due to the timing of orbital overpass. The data also contain false-positive detections, which users reported as frustrating because responding to fires could be expensive and time-consuming, especially in remote areas.

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Table 1. Respondents indicated which systems they used or developed; the number of mentions is a tally of how many people mentioned the system. We grouped the systems by the scale of operation (global, regional, national/subnational) and monitoring focus. The system scale does not indicate the application scale, as many users working at a subnational scale use global systems. We added the country/region of origin for each tool based on the results of Google searches for the tool names respondents provided. A full table with the defined acronyms is found in Appendix S3.

System name	Total mentions	Thematic focus	Country/region of origin
Global systems			
CAMS	1	Air quality	EU
EarthMap	1	Analysis platform	EU
MBON	1	Biodiversity	EU
UN Biodiversity Lab	1	Biodiversity	EU
WorldView	1	Data platform	USA
FEWSNET	2	Drought	USA
VCI	1	Drought	USA
SarVision	1	Ecosystems/ land use	The Netherlands
Firecast	21	Fire	USA
FIRMS	27	Fire	USA
GFEWS	1	Fire	EU
GFW VIIRS	1	Fire	USA
GWIS	1	Fire	EU
Ororatech Wildfire	1	Fire	Germany
GFAS	1	Fire emissions	USA
GFED	1	Fire emissions	USA
Glofas	1	Floods	EU
Forest Foresight	2	Forest	The Netherlands
Forestwatcher	1	Forest	USA
GFW	11	Forest	USA
GLAD	16	Forest	USA
GLADS2	3	Forest	USA
Global Mangrove Watch	1	Forest	EU
JJFAST	1	Forest	Japan
RADD	4	Forest	Netherlands
Widyty	1	Marine vessels	Norway
GFS	1	Weather	USA
Zoom. Earth	1	Weather	USA
Regional systems			
MapBiomas	1	Ecosystems	Brazil
TroFMIS	1	Ecosystems	Africa
ForestFire	1	Fire	Nepal
RFMRC-SEA	1	Fire	Indonesia
CBFEWS	1	Floods	Nepal
LAFDM	1	Floods	USA
ECMWF	1	Weather	EU
National/subnational systems			
Tremarctos	1	Biodiversity	Colombia
Geobahia	1	Data platform	Brazil
SAD	1	Ecosystems	Brazil
SMBYC	1	Ecosystems	Colombia
CFFDRS	1	Fire	Canada
Cwfis	1	Fire	Canada
QUEIMADAS	3	Fire	Brazil
SATIF	1	Fire	Guatemala
SATRIFO	1	Fire	Bolivia
Suindara	1	Fire	Brazil
Wildfire Analyst	1	Fire	USA
DETER	5	Forest	Brazil
GEOBOSQUES	3	Forest	Peru
INPE	1	Forest	Brazil
PRODES	1	Forest	Brazil
Radar de Sustentabilidade	1	Spatial planning	Brazil
CyAN	1	Water	USA
GEWS	1	Water	Madagascar

Developers were increasingly incorporating the monitoring of information from multiple sensors for more complete temporal coverage and leveraging synthetic-aperture radar products to detect changes obscured by clouds in optically based alerts. Users with access to more resources supplemented alert information with observations from the field, aerial sensors, tower sensors or *in situ* cameras for validation purposes. However, many users did not have access to verification data; 20% of respondents expressed the need for alerts coupled with recent, high-resolution imagery, drone footage or enabling automated verification through *in situ* monitoring.

Respondents applied this multitude of systems in diverse ways to support conservation decisions and put pressure on the actors responsible for environmental change. The simplified user-requirements statements, which we extracted from the interview data, illustrated the applications users indicated in the survey data. These data showed that the most common CEAS application was for enforcing land-use policies (43%), followed by applications for education/awareness/engagement (32%) and finally for fire/disaster management (24%; Table 2). With few exceptions, most people used CEASs for legal enforcement and designing disincentives to deter illegal activities (e.g., legal fines, prosecution, social pressure). One example of incentives was through a payment for ecosystem services programme for community-based management of bushfires. Successful communities received financial rewards for protecting the lands degraded by fires to promote assisted natural regeneration. In another example, a national non-governmental organization (NGO) provided financial institutions with evidence of landowners illegally clearing forests to inform these institutions of individuals and companies that should not qualify for loans, an action that punished violators and rewarded landowners who were in compliance. CEASs were also used for strategic personal or business decisions-making. An example of a personal benefit was an independent cattle-herder who used satellite-based fire alerts to herd his cattle away from newly burned areas with no grass towards older burned areas where grass would be sprouting. An example of a business benefit was a buyer of beef or soy committed to sustainability who had used the forest disturbance alert information provided by a national NGO to decide which environmentally responsible owners to engage in business with.

Barriers to access and use

The collected information highlighted challenges users experienced from poor internet connectivity, cellular dead zones and unreliable electricity. Respondents indicated that the person responsible for monitoring environmental threats might need a computer or smartphone to receive or report information, or they might find the alert information difficult to interpret, especially when the tool interface did not provide text in their native language. They also found that automatically translated or AI-translated text was of poor linguistic quality.

Based on the survey, we gauged how confident users working at national to subnational scales were in their knowledge of systems. There was no statistically significant difference in the means between how female and male users rated their knowledge of the systems. However, respondents working in South America conveyed a stronger familiarity with systems compared to those working in North America ($p = 0.05$). In fact, users from South America were more familiar with systems compared to users from the rest of the world ($p = 0.04$; Fig. 2). Most strikingly, for global

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Table 2. Aggregated application categories with percentages of the number of survey respondents who indicated that they were users of conservation early-warning and alert systems by user in that category divided by the total number of responses; tally of survey responses from respondents by disaggregated category; and simplified requirements statements of use cases collected through interviews with users and developers.

Application category		Number of responses by users	Examples from interviews with developers (who, what, why?)
Land-use policies and enforcement (43%)	Informing land-use policies/ land management strategies	46	A government official in a state department uses burned area assessment and fire severity assessment to plan for fire management and restoration strategies. A park manager uses fire detections to assess the effectiveness of prescribed burns in protecting biodiversity and how to improve upon practices to best meet conservation objectives. A technician working for a municipality uses the fire risk information to control the number of permits issued for fire and forest clearing.
	Evidence of land-use violations	31	A private company adhering to deforestation commitments uses fire alerts to detect whether a fire that caused deforestation originated on the land where they have contracts with owners. The company may threaten to terminate contracts based on the farmers' actions.
	Law enforcement	23	A law enforcement officer monitors fire detections because many are set by illegal poachers to push animals towards an area where they kill or trap them. By knowing where the fires are, they know where to find the poachers to fine them and deter them from poaching in the future. A national NGO overlays forest disturbance alerts with planetary high-resolution imagery census track data to determine whether the deforestation was illegal and then gives the data to public prosecutors, who hold the government accountable for illegal deforestation. A ministry official monitors alerts and then sends out patrols or drones or interprets high-resolution imagery to validate detected changes and determine the causes in order to hold the offenders accountable.
	Patrolling	22	A protected area manager uses the fire information to monitor large parks and plan patrol routes to intervene when fires are detected and to deter future encroachment. A ranger for a protected area uses the monitoring information to report fire events and strategize patrol routes.
	Community-based monitoring	42	An Indigenous community member monitors encroachment on their lands and verifies the satellite-based alerts with photos or drone footage to provide evidence in the formal legal complaints submitted to the authorities responsible for deterring these activities for the purpose of upholding the community's land rights. A farmer in a remote area knows that the standard fire service takes too long to arrive in their remote location, so they monitor nearby fires and extinguish them before they get too big and destroy their crops and properties.
Education/awareness/ engagement (32%)	Public awareness	44	An advocacy group uses forest disturbance alerts to publicize forest degradation due to illegal activities enabled by the government to bring attention to government corruption.
	Education	44	A local NGO hosts community meetings and sets up a generator and projector to explore maps of satellite-detected fires and discuss the importance of fire prevention practices.
	Community engagement	36	An NGO worker uses fire alerts to detect when fires were set outside the normal burning season. They send a team to verify the fires with planes and notice that the fires were set by recent immigrants who were using their traditional practice in a different landscape, causing fires to burn out of control. The NGO talks with the communities about the different timing for burning in their new environment to avoid future fire disasters.
Fire/disaster management (24%)	Fire prevention	37	A technician in the municipality uses the fire risk information to control the number of permits issued for fire and forest clearing to prevent fire disasters. A government technician uses fire alerts to detect fires and calls the landowners to ask them whether they are aware of the fire and if it is under control.
	Active fire management	35	An officer in the fire service combines fire hotspot data with lightning strikes data and smoke plumes from satellite radar images to determine whether the hotspot detection is valid before sending a fire-fighting team out to the remote areas to be strategic with limited resources. A technician in a national government receives fire alert data from a global system, analyses the data to prioritize actions, then disseminates commands to local fire authorities in the local language. A technical manager in a utility company uses the fire alert data to monitor fires burning close to utility lines and sends a team to put out the fire before it causes a power outage. A technician in a natural resources ministry monitors the fire alerts and sends information directly to staff on patrol to intervene on the ground.

(*Continued*)

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Table 2. (*Continued*)

Application category		Number of responses by users	Examples from interviews with developers (who, what, why?)
	Emergency response	21	A technician in the government uses fire hotspots along with demographic data on vulnerable populations to prepare briefings on natural disasters for staff at the higher levels of government, including the prime minister, to inform strategic decisions and reduce disaster risks.
	Public safety	1	A private citizen uses the fire hotspot maps on a mobile device to monitor where fires are moving and assess their own personal risk, whether this is preparing to evacuate or determining routes to avoid while in transit.
Other (1%)	Financial disincentives	0	A researcher at an NGO based in a tropical country monitors illegal forest activities by local producers to report the offenders to the commodity companies sourcing from these producers to pressure companies to terminate contracts with offenders and disincentivize illegal deforestation. A national NGO provides financial institutions with evidence of landowners illegally clearing forests so banks will not lend to those owners who seek to purchase more land with financing, an action that punishes violators and rewards landowners who are in compliance.
	Monitor disbursements of PES	1 (free-form survey)	A PES manager uses active fire alerts to monitor the success of a PES programme that encourages community-based management of bushfires. Successful communities receive financial rewards (PES) for protecting the degraded lands for assisted natural regeneration.
	Strategic decisions for personal/business gain	0	A cattle-herder uses fire alerts to herd their cattle to areas with fresh grass several weeks after a fire and to avoid recently burned areas that are still charred. A buyer of beef or soy committed to sustainability uses the forest disturbance alert information provided by a national NGO to decide which environmentally responsible owners to engage with in business.
	Uncategorized without examples	2 (free-form survey)	'Agricultural insurance.' 'Inform sampling strategies.'

NGO = non-governmental organization; PES = payment for ecosystem services.

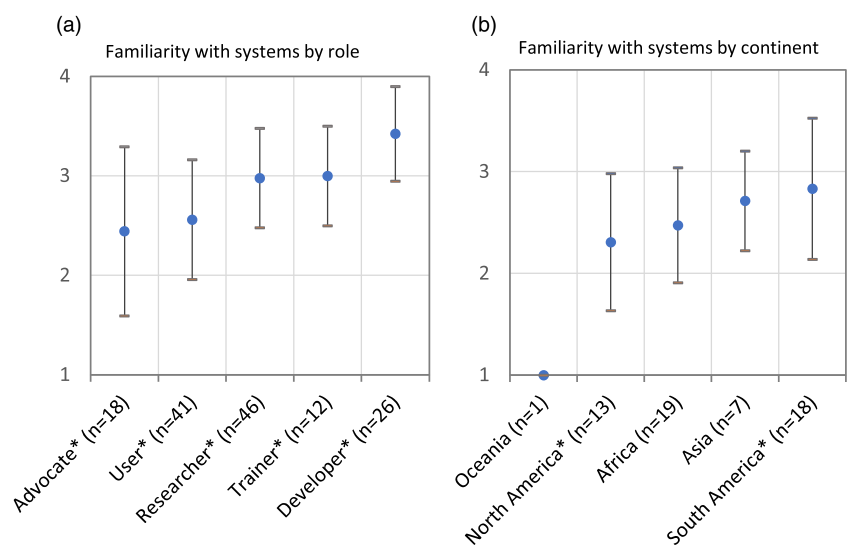

Figure 2. Mean and variance of self-described familiarity with systems by (a) users' roles and (b) the continent of work. The quantitative values for familiarity were scored from 1 to 4, with 1 = not familiar, 2 = somewhat familiar, 3 = very familiar and 4 = expert. Asterisks indicate significant differences in the means ($p < 0.5$) according to paired t-tests. For (a) the only paired t-tests that were not significant were (trainer, researcher) and (user, advocate). For (b), the means for North America compared to South America were the only differences that were statistically significant.

users, only four of 41 rated their knowledge of systems as 'expert', despite 70% having worked in their profession for 11 or more years.

As for suggestions to improve CEASs, the respondents suggested improving access and awareness of these tools through capacity-building, boosting their discoverability, leveraging social media to increase public awareness and demonstrating their value to policymakers (Table 3). For smartphone users, they recommended disseminating alerts through mobile messaging apps (e.g., WhatsApp, Telegram) and directly integrating them with navigation applications (e.g., Apple Maps) or communicating through social media applications. One developer highlighted a novel smartphone application for active fire management whereby the emergency response agency texted to firefighters the QR codes that link to online maps so that they could easily view and share fire locations on their smartphones. Some participants suggested that non-smartphone users require SMS messaging without images, and in remote regions alerts should be radioed directly to local authorities. One user recommended establishing partnerships or agreements with local utility companies to expand cellular coverage, stabilize electricity supply or reduce cellular costs for

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Table 3. Solutions to barriers to conservation early-warning and alert system use indicated by respondents.

Receiving timely alert information
‣ Arrange agreements with utility companies to provide internet and electricity
‣ Transmit lighter information (i.e., simple telephone SMS without images)
‣ Use radio transmission for alert information
‣ Provide location information in a format that could be automatically integrated into a mobile navigation app
‣ Involve local authorities to transmit information
‣ Connect with citizen science apps or mobile monitoring systems
‣ Provide multiple alert systems that complement one another in terms of completeness/accuracy
‣ Improve delivery mechanisms such as application programming interfaces, SMS, Telegram and WhatsApp
‣ Improve monitoring frequency to support disaster response systems
‣ Integrate into additional ArcGIS and fire modelling platforms to help streamline data use
‣ Create a specific information channel for public access
Improving utility of alert information
‣ Include area estimates of the alerted tree-cover loss
‣ Add the potential drivers of threats to indicate what might be causing them
‣ Improve alert accuracy for a wider variety of landscapes, dry forests and non-forest land cover
‣ Stratify and filter alerts according to the recipient's needs
‣ Let each type of user receive alerts that are relevant for their mandate and mission
‣ Include associated confidence for each alert
‣ Provide more current images to identify the type of forest, affected area and topography
‣ Provide access to recent, high-resolution satellite imagery, *in situ* cameras or drones with alerts
‣ Provide free access to daily images in high resolution
‣ Produce concise and actionable reports
‣ Distinguish forest degradation due to illegal activities versus that due to state-sanctioned activities
‣ Include metadata with alerts
‣ Add predicted deforestation
‣ Increase the use of ground truthing and hybrid-source systems
‣ Communicate threats with animations to show changes over time
‣ Link land ownership or parcel data to help filter only relevant alerts
‣ Reduce false positives in dry forests, non-forest land, wetland, and mangrove ecosystems
‣ Combine alerts from multiple alert systems to improve confidence in alerts and completeness
‣ Be alert to emerging trends (hotspots) such as increasing frequency of threats and provide context for these trends
‣ Improve information reliability and accuracy to help increase confidence in the data
‣ Send alerts in shapefile and *Excel* (tabular) file data
‣ Improve local fuel models, which are not described well in fire spread models
Increasing resources/capacity/awareness to respond to information
‣ Engage policymakers regarding the alert information and its importance
‣ Build different modules (platform approach) of systems to facilitate handover to local or national authorities to host system
‣ Integrate alerts with their existing (administrative) systems for tracking field investigations
‣ Provide more training and capacity-building to use tools
‣ Create alert systems that include metrics for cost–benefit analysis (i.e., avoided losses of carbon or air pollution)
‣ Increase outreach efforts to raise awareness of existing products
‣ Get buy-in from governments and decision-makers that these systems are evidencing change on the ground
Improving design
‣ Design user-friendly alerts with simple, non-technical text in the native language
‣ Co-design systems with input from local communities
‣ Create more open-access, free tools
‣ Use colour codes for people who have trouble reading
‣ Gather requirements from on-the-ground users
‣ Design understandable symbology of alerts on the map
‣ Use local data, not just global or national data, which are often outdated
Making information actionable
‣ Enhance traceability for linking information to action
‣ Work within decision support frameworks and co-design action plans
‣ Coordinate with legal agencies to get the information they need to act upon the alerts
‣ Provide driver-specific alerts to make it clear which authorities are responsible for acting on the alerts
‣ Include multi-hazard criteria for better prioritization, risk and opportunity analyses
‣ Reward reporting of illegal activities, taking great care to ensure whistleblower protections
‣ Work with local-level government bodies in rural areas

devices used by law enforcement or communities for monitoring and enforcement.

In addition to making alert information more accessible, they suggested making the data easier to interpret. While new devices, enhanced connectivity and social networking can help improve access to alert information, improved technology design based on people's needs could help users leverage the information in CEASs. One developer commented, 'We tend to come up with the technology first and then backfill with the people component, and honestly, the people component should be the first priority. And then this mastery of technology that we have at our disposal should then be designed to meet those requirements from the ground-up approach.' Other respondents stressed that co-designing systems with input from local communities and gathering requirements from on-the-ground users were essential to how decision-makers interpret and use information effectively. One developer recommended using the tools to bridge knowledge systems and effectively engage with communities to co-develop solutions, especially when working with communities on sensitive topics, such as introducing fire surveillance technologies to communities with existing cultural fire practices.

Collectively, respondents recommended user-friendly alerts with simple, non-technical text in the native language (not translated by AI) or with symbols and colours for people who do not read. In addition, they suggested that providing contextual information with alerts can aid in decision support and help users prioritize responses. One interviewee commented, '. . . one of the major issues anyways to have, [is that] you need to prioritize somehow. Otherwise, you [are] often overwhelmed by the sheer amount of alerts you get.' To help them prioritize, respondents requested more detailed alert information about the land-cover type, cadastral information and the cause of the environmental change. Overall, the recommendations for improving systems between users and developers had substantial overlap. However, there were a few notable differences in priorities by role. System developers and researchers suggested improving alert accuracy as a top priority to increase use, whereas users, advocates and trainers proposed improving alert details as a top priority.

Barriers to action

Overall, the survey respondents valued CEASs as cost-effective solutions to improve coordination, resource allocations and strategic responses to ecosystem threats. The CEASs most

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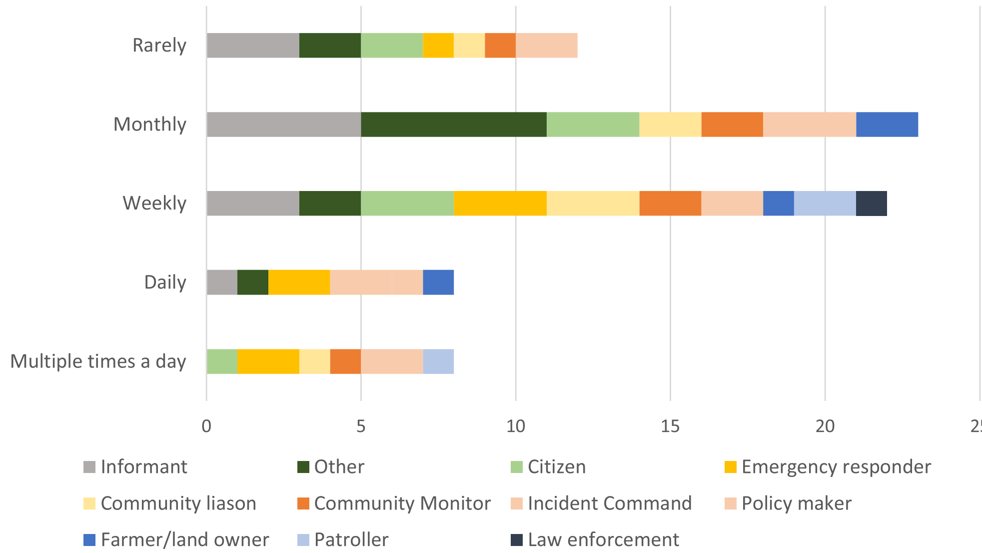

Figure 3. Bar chart of how frequently users responded to information from a near-real-time satellite-based monitoring system according to the users' roles.

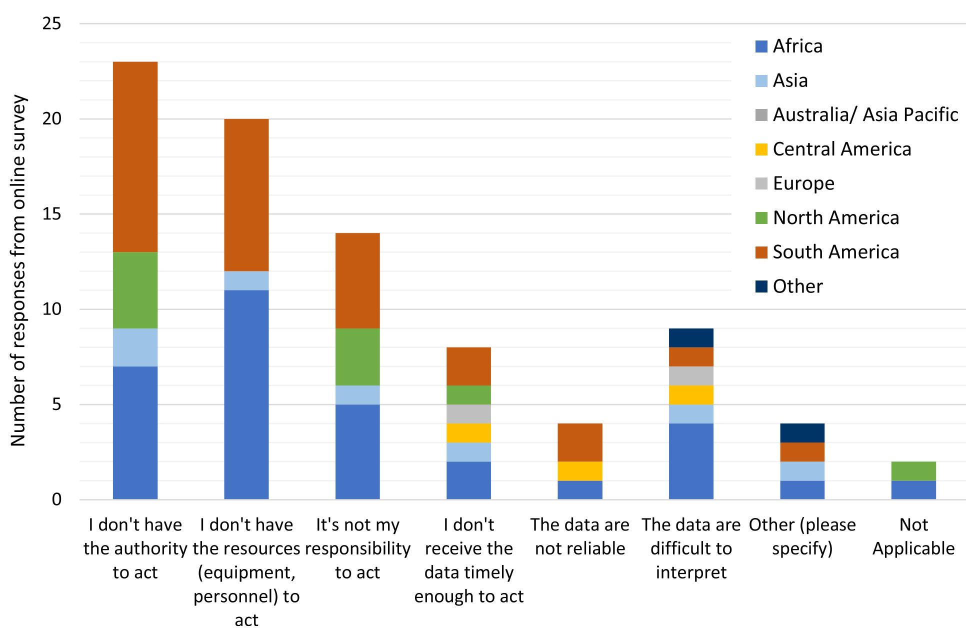

Figure 4. Bar chart of numbers of respondents (aggregated by continent) giving different reasons why they could not respond to near-real-time alert information.

frequently mentioned by survey participants (Table 1) send alert information at a frequency of sub-daily to weekly. Yet, the survey results indicated that most CEAS users accessed the information on a weekly or monthly basis (Fig. 3).

Respondents indicated significant barriers preventing users from acting upon information received from CEASs. They identified lack of authority to act upon information and insufficient resources as two top barriers preventing users from acting upon the information. The barriers selected by users differed depending on the continent of use. Most users working in the Americas and Africa indicated that lack of resources was a significant barrier. Users working in Asia and Africa reported that not having the authority to act upon information was the most difficult barrier to overcome. Users working in Europe indicated that the most challenging obstacles to using these data were the lack of timeliness and the alert information being too difficult to interpret (Fig. 4). Additional barriers that respondents suggested in the free-form responses on the survey included power outages, fuel shortages and faulty equipment. Developers also indicated that staff turnover and government bureaucracy were barriers to maintaining the staff capacity for system use.

Respondents recommended providing incentives to use systems, such as investing in local resources to respond to alerts, as consequential to enabling CEAS use. One successful example of incentives was the World Resources Institute's small grants programme, which funds training, equipment and other support to non-profit organizations to improve the use of their alert information. Other suggestions included better engagement and coordination with legal authorities to ensure they can act upon this information. Based on the experiences of multiple developers, teaching a user how to use a system is insufficient; instead, developers suggested crafting action plans with users regarding

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how they respond to the information they receive. One innovative idea was developing an alert tracking system for accountability that would track the movement of information and actions along the decision timeline in order to identify information bottlenecks or communication breakdowns. Alert information could be integrated into the administrative tracking/reporting systems for local law enforcement agencies to track information and expedite responses.

Risks and opportunities with surveillance technologies

Utilizing the surveillance capacities of CEASs to increase the accountability of the actors driving environmental change was a top priority for respondents. They reported stories of communities, media and civil society organizations leveraging this information to pressure governments and corporations to address environmental degradation. For example, Indigenous communities use satellite information as hard evidence of illegal activities so that government officials cannot dismiss their claims. The results also provided evidence of citizens exploiting satellite surveillance to their advantage. For example, the number of calls to a 'tip hotline' to report illegal fires increased when the local government also started using MODIS hotspot data to fine landowners for unlawful burning. Farmers were more comfortable reporting their neighbours to this tip hotline as doing so avoids the creation of social conflict within the community.

In addition to these successful applications of CEASs, respondents raised concerns about privacy, autonomy and resources supporting foreign systems over local solutions. Some respondents were concerned about their governments' use of surveillance to punish and further marginalize smallholder farmers, migrants or Indigenous peoples and local communities. Another risk that respondents raised was that of external actors such as civil society organizations, private companies and development agencies pushing technology solutions. One interviewee said, '[International organizations] come from high in the sky with their nice, beautiful, well-funded projects, and they don't engage with those [in-country] who are already making the efforts towards the same objectives. Because perhaps they already have beautiful databases and products ready to go. And together, you can bring the resources together to build the channel for their distribution.' Many developers we interviewed stressed the importance of local partnerships and building trust with local actors. However, with so many systems having been developed by an array of actors, participants expressed frustration with the duplication of efforts, the push from funders to innovate instead of supporting the operation of existing solutions and the Global North financing multiple in-country systems.

Users and developers expressed frustration that private-sector solutions were stifling innovation and suppressing technician capacity development. Respondents from South America, where the capacity to build a system is strong, expressed frustration with private-sector companies building proprietary solutions to create dependencies on licensing, subscription services or expensive high-resolution imagery. However, one technician working for an environmental department in Mato Grasso, Brazil, found proprietary alert systems to be cost-effective solutions. They contracted a private company to produce forest disturbance alerts so that they could monitor land-use infractions by landowners. The income that the government agency generated annually from fining landowners for land-use infractions exceeded the service costs. Overall, these results highlight the context dependencies of the risks and opportunities with SBM that require close examination for every application.

Discussion

Our research documented how CEASs inform broad actions by diverse users for addressing environmental changes. The flexibility of CEASs for broadly scoped applications was evident from the number and variety of tools used, including the diversity of users ranging from community members to civil society organizations, government agencies and the media. While these tools have widespread use, our study indicated that CEASs were more familiar to users in South America. This is probably due to the number of tools developed in South America and also the published studies evaluating those tools (Finer et al. 2018, Musinsky et al. 2018, Weisse et al. 2019, Mullan et al. 2022, Assunção et al. 2023). We recognize that tools from South America are better represented in this study when compared to those from other regions (Table 1), which may be biased due to the distribution channels for the survey data. Furthermore, since we aimed to cast a wide net globally, our results only captured a few data points from each country, and those responses are far from representative of each country. For example, the median number of responses by country was 2.0, the mean was 3.8 and only three of 38 countries represented contributed more than 10 responses (Colombia, Madagascar and the USA).

Our results disproportionally represented examples and stories of CEASs used for their monitoring capabilities, not their forecasting capabilities. Although forecasting tools were represented (e.g., Forest Foresight, SATRIFO and Wildfire Analyst, among others; Table 1), forecast applications were not represented in the users' stories, indicating an opportunity for a focused study of CEAS forecasting tools. The most popular uses of monitoring and alerting tools reported by participants in this survey were to deter environmental crimes through law enforcement, to spotlight the accountability of culprits and to leverage finance mechanisms for punishments. However, enforcement applications in regions with unclear forest governance and tenure are complicated. Even with clear governance policies, the adoption of tools for community use must be complementary with enforcement at other scales – namely municipality or district scales – or the intervention may be ineffective (Slough et al. 2021). In addition, CEASs that leverage satellite data are surveillance technologies that state actors can use to marginalize disadvantaged communities by bolstering overreaching policies through the erosion of a community's right to self-governance (Adams 2019, Pritchard et al. 2022).

CEASs are underutilized to support policy compliance or incentivize actions in support of environmental goals, which may facilitate conservation activities in areas with complex land tenure systems. Based on evidence from two case studies in Africa, Shea (2022) found that NRT monitoring forest disturbance alerts were most effective when used with incentives. Slough et al. (2021) found that incentives to verify NRT forest disturbance alerts increased the frequency of reporting of forest disturbances by the assigned community monitors. When designing an incentive programme, the incentive should be tailored to each community. Each community faces different challenges regarding accessing forests or internet access, and therefore the task of monitoring poses larger burdens on some communities than others. An incentives programme should compensate participants fairly and consider not only the time commitment but also other burdens and associated risks (Cappello et al. 2022).

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Despite widely reported applications of CEASs, participants indicated barriers to the access and use of the systems as preventing efficient use of the CEASs, in terms of both underutilizing the low-latency data they provide and enabling a response to the delivered information. The barriers reported here resonate with those highlighted by system developers (Davies et al. 2009, Finer et al. 2018, Musinsky et al. 2018, Weisse et al. 2019). Many CEAS developers have innovated based on users' feedback. For example, Reiche et al. (2024) addressed users' concerns regarding confidence in forest disturbance alerts by combining disturbance alerts from multiple systems and weighting alert confidence based on the spatial and temporal proximity of the alerts. Not only did combining alerts improve alert detection, but it also reduced the number of false positives. Musinsky et al. (2018) recognized the challenges users faced in low-bandwidth areas and designed their fire alerts to minimize data size and enable email delivery to avoid the burden of downloading from a server or of loading heavy webpage content through the use of interactive web maps. Many other examples can be borrowed from other disciplines in the literatures on early warning for disaster risk reduction, humanitarian early-warning systems and climate services (Tabor & Holland 2021).

One theme throughout the present study was the emphasis on the importance of co-design, co-development and collaboration from users and developers in the Global South and the recognition of the risks of excluding communities (Jarvis et al. 2020). Similar to other studies focused on single tools or disproportionately representing different user groups (Davies et al. 2009, Jepson & Ladle 2015, Finer et al. 2018, Musinsky et al. 2018, Weisse et al. 2019, Shea 2022), our study documented the many tools that can be exclusionary in both big and small ways, ranging from infrastructure inequities preventing access, to insufficient resources or a lack of authority to act, to simple design flaws. One example of a successful collaborative approach is the field data collection app Sapelli, which uses a co-design process to apply a users' local languages and customized icons to build more intuitive and comprehensible interfaces for illiterate and non-literate users (Moustard et al. 2021). While there is momentum for co-designing technologies, there remain structural inequalities to technology ownership and creation (Costanza-Chock 2020). The collaborative production of CEASs is an important first step towards addressing digital inequities. However, more deliberate measures are needed to equalize global CEAS ownership. We encourage the conservation community to innovate on pathways forward.

Our study explored how barriers to tool access affect users in different roles and places of work. Targeted funding is required to reduce the barriers facing all users to access CEASs and to enable actionable responses. For example, more investments in infrastructure, resources, equipment, capacity-building and knowledge-sharing are needed to disrupt structural inequities in technology access and to link information to action. While capacity-building is a standard approach to increasing tool use, this study showed inequities in capacity and awareness stemming from barriers to technology access, exposure to tools and training. Perhaps some of the lack in familiarity with systems of even seasoned professionals results from the fast-paced technology advances, the frequent tool iterations and the growing number of tools developed for conservation applications. Therefore, capacity-building must be sustained with continuing effort and should include co-designing tools and co-developing plans for responding to alerts in the context of users' roles. The conservation community can glean examples from community-based resilience and disaster risk reduction on co-developing community action plans (Saja et al. 2019).

There is a growing literature on conservation decision triggers and developing management plans to respond to monitoring information within the scope of organizational capacities (Cook et al. 2016). Aligning tools to policy objectives and identifying a champion for the tool within the decision-making agency/organization facilitates the use of conservation decision-support tools (Gibson et al. 2017). Furthermore, entities developing or promoting CEASs should work with partner institutions and user communities to create action plans for responding to this information by leveraging multiple forms of evidence, including traditional knowledge and practices (Kadykalo et al. 2021). More research is needed to evaluate strategies for CEAS applications in different political, socioeconomic and cultural contexts.

However, those promoting CEASs should consider how technology can reinforce social inequities or violate civil liberties (Arts et al. 2015). Given the critiques of conservation efforts prioritizing the protection of biodiversity over people (Arts et al. 2015, Adams 2019, Speaker et al. 2022), the application of conservation technologies requires careful consideration. Conservation actors need to understand the risks of introducing technologies, assess these risks and responsibly use technologies by gaining consent for surveillance, safeguarding privacy and respecting peoples' rights (Sandbrook et al. 2021, Pritchard et al. 2022). When co-developing data ownership plans with communities and engaging with the people directly managing natural resources, conservation actors should adhere to data governance guidelines and best-practice principles for Indigenous data governance such as the collective benefits, authority control, responsibility and ethics (CARE) principles (Carroll et al. 2021, Jennings et al. 2023).

Conclusion

CEASs inform actions to address environmental change when decision-makers have adequate access, resources and motivation to act. In this first comprehensive study of SBM for conservation applications, we used a mixed-methods approach to understand who uses CEASs and in which decision-making contexts. The myriad systems in use reflect the systems' utility for diverse applications. The growing number of systems also reflects funders being compelled to produce novel technological solutions. Investments in infrastructure, resources, knowledge-sharing and incentivizing tool use are needed to fully exploit the current suite of CEASs. While CEASs can be mechanisms for effecting change from global to local scales, external actors supporting CEAS should better understand local contexts and co-develop solutions that maximize their use while reducing risks to people. With careful application and improved coordination, CEASs can potentially play a critical role in supporting global sustainability.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/S0376892924000274.

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