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INTERDISCIPLINARY PERSPECTIVES

Opportunities for improving conservation early warning and alert systems

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Abstract

Conservation early warning and alert systems (CEAS) provide tremendous opportunities to inform strategic and effective environmental responses. However, these systems are not systematically evaluated based on how they are contributing to conservation outcomes. We survey the current state of systems enabled by satellite monitoring to support tropical forest management and highlight their recent proliferation and the sparse evaluations of these systems in terms of user adoption and application for improving conservation decisions. To guide practitioners, funders and policymakers to choose the appropriate tool for the application, we distinguish two types of CEAS, *Rapid Response* and *Targeted Response*, characterized by the user application and the timeframe for decision-making. These tools are distinct from monitoring tools used for policy and planning which require routine, high-accuracy and quantifiable estimates of land cover change. We see a need for more systematic evaluations quantifying their environmental and socioeconomic benefits and improved indicators measuring progress toward achieving conservation outcomes. To inform system developers, we summarize best practices for increasing system adoption and use gleaned from seasoned applications of early warning and alert systems for conservation and humanitarian applications. Engaging diverse stakeholders, building permanent capacity, increasing accessibility and interpretability of the information, and communicating the information value to decision-makers help root these systems into decision-making processes. Incorporating local knowledge and on-the-ground monitoring information from stakeholders can improve alert accuracy while respectfully honoring local knowledge and garnering stakeholder trust in the systems. Strengthening cross-institutional networks, building political support, and allocating adequate resources empower decision-makers to act upon the information. Addressing today's urgent conservation challenges requires linking accessible, trusted and effective CEAS to empowered people taking conservation actions.

Introduction

How we address the societal challenges of today has important implications for future global well-being. The development and conservation communities, along with private and public sector actors, are grappling with how to meet ambitious global targets for sustainability. Satellite monitoring and information technologies provide tremendous opportunities to inform strategic and effective environmental responses. International donor organizations and governments have used early warning and alert systems (EWS) for over three decades for humanitarian applications to inform rapid, strategic and effective responses to conflict, disease, famine and natural disasters (Whittall, 2010; Garcia and Fearnley, 2012; Pulwarty and Sivakumar, 2014). An EWS detects a threat and issues alert information to prompt an actionable response to mitigate the threat (Garcia and Fearnley, 2012). In recent years, the conservation community has fostered a separate set of conservation early warning and alert systems (CEAS) that utilize the near real-time (NRT) monitoring capabilities of earth observations to detect ecosystem threats and disseminate alerts through web and mobile technologies. Earth observations are information from satellite data, drones, in-situ sensors, and field-based observations used for biophysical monitoring purposes. For this paper, we focused on CEAS that use satellite data primarily to support tropical forest management and conservation.

CEAS play a critical role in increasing the visibility of global change by delivering time-sensitive information to decision-makers who take measures to reduce the destruction of ecosystems providing services and supporting human well-being (Lynch et al., 2013). In this paper, we review the current suite of CEAS, their applications, and evaluations to improve decision-making for conservation outcomes. We present a typology of systems to guide practitioners, funders and policymakers in choosing the appropriate tool for the application. We also review lessons learned from operators of CEAS and of humanitarian EWS to help system developers improve the adoption and use of CEAS for conservation applications. Given the recent increase in the development of CEAS to help achieve conservation and sustainable development targets, we see this review exercise as particularly relevant for the future refinement, adaptation and implementation of such systems.

Current Suite of CEAS

Due to the sparse published literature on the current suite of CEAS, we compiled information on CEAS from various sources, including from peer-reviewed literature, gray literature and direct discussions with system developers and conservation practitioners working with these tools (Table 1). We acknowledge that the CEAS presented in this paper is not a comprehensive list. The remainder of this section reviews the recent growth of CEAS, including the spectrum of new NRT satellite products and the expanding diversity of users and conservation applications.

Fire monitoring

The first generation of CEAS applications in the early 2000s used thermal anomalies detected by coarse spatial resolution satellite sensors with multiple observations per day to monitor deforestation fires and disseminate fire locations to local decision-makers. These decision-makers included protected area managers, conservation practitioners, communities, policymakers and researchers (Musinsky et al., 2018). The Fire Information for Resource Management System (FIRMS) and Conservation International's Fire Alert System (FAS) were two pioneering and complementary systems that prioritized information accessibility by sending data in GIS friendly and text formats directly to users' email inboxes (Justice et al., 2002; Tabor and Hewson, 2018). FIRMS aimed to enhance the user experience with the satellite information by producing refined information that is easy to use yet still timely to support a range of users and broader applications (Davies et al., 2009). FAS used FIRMS data and further refined data delivery for conservation applications in developing countries by providing customized subscriptions to increase accessibility. For example, FAS alerts accommodated a user's language of choice and filtered fire information with biodiversity, land cover and land governance data to increase data relevancy and reduce data size. FAS also emphasized user-buy-in and 'co-ownership' of systems with government agencies to build trust in the data, and continued engagement and in-country capacity building to support tool adoption (Musinsky et al., 2018). Today, several global and national alert systems disseminate active fire data for a variety of applications including enforcing conservation and development policies, promoting public awareness of environmental issues, strategizing patrols of protected areas, and facilitating fire management (Davies et al., 2009; Musinsky et al., 2018).

Forest change monitoring

NRT forest change monitoring emerged soon after NRT fire monitoring. In the early 2000s, the government of Brazil invested in earth observation monitoring systems to address the high rates of deforestation in the Brazilian Amazon. After reaching peak deforestation rates in 2004 (Fearnside, 2017), the Brazilian government initiated an action plan to reduce deforestation through an integrated framework for decisions related to policy, management and enforcement. Brazil developed a suite of monitoring tools to help enforce environmental governance and inform public policies (Diniz et al., 2015). These tools, coupled with strategic forest management policies, successfully reduced deforestation rates by 75% in the decade following the federal action plan, 2004-2014 (Laurance et al., 2016). In 2016, Brazil's CEAS detected escalating Amazonian deforestation rates and then again, in 2019, alerted the world to the onset of a devastating fire season, thus highlighting the utility of CEAS in making environmental change information accessible and transparent (Crouzeilles et al., 2017).

Brazil's operational forest disturbance alert system, DETER (for its acronym in Portuguese) relies on high temporal resolution but coarse spatial resolution (250-m to 5-km pixel) satellite data inputs (Shimabukuro et al., 2013), similar to global forest disturbance detection

Table 1. CEAS with names of systems, operating organization, country of origin, counties served, type of monitoring information, time frame of operational monitoring, and type of CEAS (RR = Rapid Response; TR = Targeted Response). This table does not include all the systems that may exist.

System	Full name	Operator	Country of origin	Geography	Monitoring	Operational	Type of CEAS
AFIS	Advances Fire Information System (AFIS)	Council for Scientific and Industrial Research's (CSIR)	South Africa	Global	Active fires, fire weather	2010 to present	RR
DETER	Sistema de Detecção do Desmatamento em Tempo Real na Amazônia	National Institute of Space Research (INPE)	Brazil	Brazil	Forest disturbance	2004 to present	RR
EFFIS	European Forest Fire Information System	European Space Agency	European Union	European Union	Active fires	2000 to present	RR
FAS	Fire Alert System	Conservation International	USA	Bolivia, Indonesia, Madagascar, Peru	Active fire	2002 to 2012	RR
Firecast	Fire and forest monitoring and alert system	Conservation International	USA	Bolivia, Colombia, Ecuador, Indonesia, Madagascar, Peru, Suriname	Active fires, fire weather	2012 to present	RR
FIRMS	Fire Information for Resource Management System	NASA	USA	Global	Active fires	2003 to present	RR
FORMA	Forest Monitoring for Action	World Resource Institute	USA	Global	Forest disturbance	2006 to 2017	RR
Geobosques	Geobosques	Ministry of Environment (MINAM)	Peru	Peru	Forest disturbance	2017 to present	RR
GEOSERFOR	GEOportal de la infraestructura de datos espaciales del Servicio Nacional Forestal y de Fauna Silvestre	Ministerio de Agricultura y Riego	Peru	Peru	Active fires	2018 to present	RR
GFW	Global Forest Watch	The World Resource Institute	USA	20+ countries	GLAD forest disturbance	2015 to present	RR
GFW Fires	Global Forest Watch Fires	The World Resource Institute	USA	Global	Active fires, fire weather	2014 to present	RR
GFWED	Global Fire Weather Database	NASA Goddard	USA	Global	fire weather	2017 to present	RR
GLAD	Global Land Analysis & Discover	University of Maryland	USA	20+ countries	Forest disturbance (30-m)	2015 to present	RR
GWIS	Global Wildfire Information System	Europeans Unions' Joint Research Centre	European Union	Global	Active fires, fire weather	2016 to present	RR
JJ-FAST	JICA-JAXA Forest Early Warning System in the Tropics	JICA/JAXA	Japan	Global tropics	Forest disturbance (50-m)	2016 to present	RR
MAAP	Monitoring the Andean Amazon	Amazon Conservation	USA	Bolivia, Brazil, Colombia, Ecuador, Peru	Deforestation (<3 m)	2015 to present	TR
MAPBIOMAS Alerta	MAPBIOMAS Alerta	MapBiomas	Brazil	Brazil	Deforestation (<3-m)	2018 to present	TR
Mighty Earth	Mighty Earth Rapid Response Monitoring System	Mighty Earth	USA	Indonesia, Malaysia, Ghana, Côte d'Ivoire	Deforestation, post-deforestation land use	2017 to present	TR

(*Continued*)

Table 1. Continued.

System	Full name	Operator	Country of origin	Geography	Monitoring	Operational	Type of CEAS
Queimadas	Queimadas	National Institute of Space Research (INPE)	Brazil	Brazil	Active fires, fire weather	2017 to present	RR
QUICC	Quarterly Index of Cover Change	NASA Ames/California State University Monterrey Bay	USA	Global	Forest disturbance	2001–2016	RR
SAD	Sistema de Alerta de Desmatamento	IMAZON	Brazil	Brazil	Forest disturbance	Early 2000s to present	RR
SAI	Sistema de Alerta de Incendios	National Commission for the Knowledge and Use of Biodiversity (CONABIO)	Mexico	Mexico	Active fires, fire weather	Early 2000s to present	RR
SATA	Sistema de Alertas Tempranas	Ministry of Environment Ecuador	Ecuador	Ecuador	Forest disturbance	2018 to present	RR
SATRIFO	Sistema de monitoreo y alerta temprana de riesgos de incendios forestales	Fundación Amigos de la Naturaleza (FAN)	Bolivia	Bolivia	Active fires, fire weather	Early 2000s to present	RR
Sentinel Hotspots	Sentiel Hotspots/Digital Earth Hotspots	CSIRO/Department of Defense/Australian Government	Australia	Oceania	Active fires	2003 to present	RR
SiPongi	Land and Forest Fire Monitoring System	Indonesia	Indonesia	Indonesia	Active fires, fire weather	2000's to present	RR
SIRAD-X	Near real-time deforestation radar monitoring system	Instituto Socioambiental	Brazil	Xingu Basin	Deforestation	2018 to present	TR
SMByC	Colombian Forest Monitoring System	Institute of Hydrology, Meteorology and Environmental Studies	Colombia	Colombia	Forest disturbance	2018 to present	RR
Terra-i	Terra-i	International Center for Tropical Agriculture (CIAT)	Colombia	Latin America + global tropics	Forest disturbance	Early 2000s to present	RR
Vulcain	Vulcain	Government of New Caledonia	New	Caledonia	New Caledonia	Active fire, fire weather, burned area	
2019-present	RR						

systems that emerged in the past decade, (e.g., Reymondin et al., 2013; Potter, 2014; Wheeler et al., 2014). The upgraded DETER-B system, operational since 2013, now detects forest changes at 60-m resolution (Diniz et al., 2015). This advancement highlights a trend in operational forest disturbance alerts shifting to moderate and finer spatial resolution forest change alerts to improve small-scale change detection.

Global Land Analysis and Discovery (GLAD) is the first operational forest disturbance alert system detecting tree cover change at 30-m resolution (Hansen et al., 2016). GLAD alerts are used by government agencies, conservation practitioners, and Indigenous peoples and local communities (IPLCs) to report illegal forest activities, strategically manage protected areas, assert land rights, monitor conservation agreements, and elevate public awareness of environmental change (Weisse et al., 2019). Weisse et al. (2019) further identified ensuring adequate financial support, increasing cross-institutional coordination, and investing in building the technical capacities of personnel as critical to the successful uptake of GLAD alerts for improved conservation outcomes.

Recent trends in CEAS

Technological advances in cloud computing, storage capacity and interactive web design enabled new platforms for data dissemination and visualizations, such as the World Resources Institute (WRI)'s Global Forest Watch (GFW). GFW aggregates a variety of geospatial data assets and provides products to meet the needs of different users, for example, dashboard analytics of deforestation trends, fire and forest disturbance alert subscriptions. GFW's mobile application, *Forest Watcher*, disseminates forest disturbance alerts and facilitates mobile data collection. WRI launched GFW in 2011, providing a comprehensive resource of spatial data for global-scale monitoring of changes in forests (Musinsky, 2014; De Sy et al., 2016). Furthermore, the number of satellite land monitoring systems continues to multiply as countries establish national forest monitoring systems (NFMS) for reporting on Nationally Determined Emissions for the United Nations Framework Convention on Climate Change (UNFCCC). Between 2008 and 2018, a strong focus on national capacity building in 16 tropical countries enhanced their capacities for routine analyses with satellite monitoring data (FAO, 2018). With new capacities to store, process and analyze satellite data, many countries (i.e., Colombia, Peru, Ecuador in Table 1) developed national CEAS to alert to forest change.

The number and variety of satellite sensors in orbit used for conservation applications have increased substantially since 2014, enabling CEAS to circumvent the spatial and temporal resolution tradeoffs of single-sensor systems by leveraging multiple sensors for monitoring and reporting change (Finer et al., 2018). Satellite constellations and cloud-piercing Synthetic Aperture Radar (SAR) also increase the opportunities for detecting change (Tabor and Hewson, 2018; Weisse et al., 2019). These advances help overcome tradeoffs between information accuracy and data latency requirements for decision-making (Reiche et al., 2018). Data latency refers to the delay between the data acquisition and availability of that data for use by decision-makers (Davies et al., 2017). For some users, a short timeframe to make decisions necessitates tools with rapid change detections and an acceptable level of accuracy related to the location, timing and quantified measurements of the change event. Often users require rapid, high-accuracy and detailed change information, but these data are associated with a lag to acquire and process the imagery to meet the application needs. Rapid alerts of detailed change information for assessments requiring targeted information at the landscape scale are possible with semi-automated processing with multiple sensors. The Monitoring of the Andean Amazon Project (MAAP) leverages multiple satellite sensors by first using coarse to moderate resolution imagery to detect forest disturbances and then investigating the driver and extent of the change using commercial high-resolution imagery at sub-3-m spatial resolution (Finer et al., 2018). The detailed change information is published online in easy to interpret reports and maps to increase accessibility and communicate environmental change to the public. MAAP's approach of identifying the drivers of land-use change is key for pressuring specific sectors, corporate actors and policies responsible for that change. In addition to increased pressure, stronger institutional capacities and support for the systems enable coordinated and effective responses (Finer et al., 2018).

Typology of Monitoring Tools

In the past decade, dozens of web-based mapping and monitoring tools have emerged for improving policy and land management (Palomino et al., 2017; Tabor and Hewson, 2018). System developers are increasingly making tools more accessible to a wide range of users by reducing computing capacity constraints and creating a variety of easy-to-use products such as web maps, reports, dashboards and mobile applications. Now the challenge facing potential users is navigating the sea of tools and choose the appropriate tool for the application. Choosing the right technology for CEAS applications often means balancing trade-offs in data quality, data latency and scale. We define low latency data as data available from under an hour and up to 6 months from data acquisition. In contrast, high latency data are products requiring intensive data processing and analysis, such as routine forest cover and land-use change maps, which may be available more than 6 months to several years post data acquisition. Based on data latency and quality, we distinguish CEAS as a subset of monitoring tools falling into two categories: *Rapid Response* and *Targeted Response* (Fig. 1). We see value in distinguishing *Policy and Planning* tools as separate from CEAS but recognize the vital role of these tools for informing a different set of conservation decisions.

Rapid response

Rapid Response CEAS provide low latency information to facilitate an immediate response to threats. Due to the requirement for rapid information, the data may have trade-offs with data quality and typically are not used to quantify ecosystem changes. For example, the GLAD alerts were designed as conservative alerts to locate

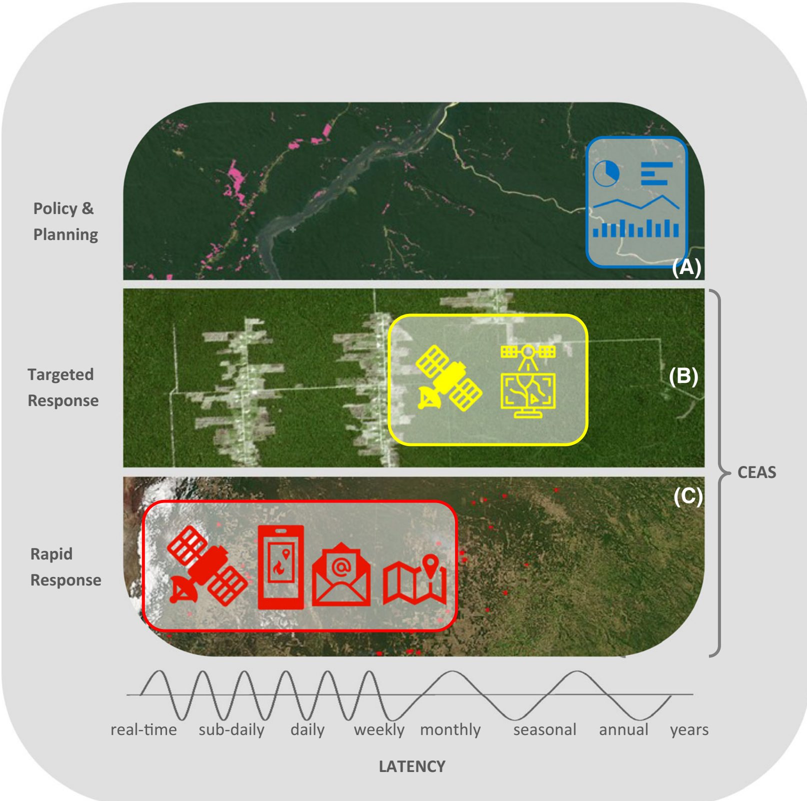

Figure 1. We distinguished types of monitoring tools for conservation applications based on latency of information (*x*-axis) and actions prompted from the information. The horizontal placement of the blue, red and yellow text boxes is associated with the *x*-axis. Policy and Planning tools require quantified change (A). The Policy and Planning background image shows 2017–2018 deforestation (pink) located near Jacareacanga, Pará, Brazil overlaid with high-resolution imagery from GFW (https://www.globalforestwatch.org/. Targeted Response tools leverage automated rapid response alerts to prompt manual analyses with high-resolution imagery and quantify change at the landscape scale (B). The Targeted Response image shows a MAAP alert to deforestation visible in high-resolution Planet satellite imagery within Mennonite colonies in Lorerto, Peru (https://maaproject.org/2019/mennonite/). Rapid Response tools use automated methods to alert to a change (C). The Rapid Response image from the MODIS Rapid Response Team shows fires in northern Argentina detected by MODIS Aqua on November 13, 2003 (https://visibleearth.nasa.gov/). Of these three types, we consider targeted response and rapid response to be CEAS based on the data latency and quality.

potential forest change and do not provide estimates of change area or attribute the proximate cause. Rapid response forest disturbance alerts from optical sensors often have high errors of omission due to cloud cover. For example, during the wet season in Peru, only 20% of the humid tropical forests are observed by Landsat 7 and 8 satellites, and this increases to only 67.5% in the dry season (Hansen et al., 2016). Active fire detection products also suffer from omission errors due to cloudiness, and they may have false positives due to sun glint angles and pixel saturation (Schroeder and Giglio, 2018). Forest disturbance alert systems are now incorporating synthetic-aperture radar (SAR) to overcome the limitation of cloud cover obscuring changes, for example, JJ-FAST (Weisse et al., 2019). Users of Rapid Response CEAS include conservation practitioners, government agencies, protected area managers and IPLCs. The information from Rapid Response CEAS are used to generate routine reports, dispatch patrols in response to threat information, and enforce land-use policies (Musinsky et al., 2018; Weisse et al., 2019). Most rapid response tools provide generalized data for multiple applications. A user may need to incorporate additional information to customize for specific applications.

Targeted response

Targeted Response CEAS include a unique set of semi-automated tools, often built upon Rapid Response CEAS, designed to overcome the tradeoffs between the information quality and data latency for a specific application. These systems use high-resolution imagery to quantify and describe change detected by Rapid Response disturbance alerts. Practitioners and researchers use the rapid, high-quality information for targeted applications, such as determining deforestation from mining operations in a landscape (e.g., MAAP), or filing legal grievances with palm oil companies to reporting illegal deforestation associated with palm oil production, (e.g., Mighty Earth, Table 1.). Targeted Response CEAS produce refined information to communicate directly with agencies tasked with policy enforcement and the responsible private sector actors; or to promote accountability by sharing the information with the general public through blogs, social media and the news media.

Policy and planning

Policy and Planning tools are not CEAS due to the high latency of information delivery but are vital systems providing data to inform longer term conservation investments and land-use policies. These tools depend on the continuity of moderate resolution, multispectral imagery from the Landsat and Sensitnel programs. Policy and planning tools produce and disseminate high-quality data that require more time to process and may become available a year or more after satellite acquisition. However, practitioners cannot efficiently assess forest loss in the tropics with optical sensors due to persistent cloud cover. When using every available Landsat scene for deforestation detection, 25% of global deforestation events are not detected in the year they occurred due to cloud cover (Hansen et al., 2013). Government agencies, conservation practitioners and policymakers use the monitoring information to design land-use policy and conservation interventions. Researchers rely on these routine and consistent forest change data for monitoring and evaluation of land use policies and practices. The private sector and conservation funders also rely on these systems to monitor investment threats/opportunities and monitor sustainable sourcing to track net-zero deforestation commitments. A few examples of policy and planning tools include Hansen et al.'s (2013) annual, global, 30-m resolution forest cover loss product and NFMS for technical assessments of Nationally Determined Contributions reporting for the UNFCCC.

Our characterization of CEAS illustrates that while all systems may use similar satellite data, the user-driven requirements determine the appropriate tool based on acceptable trade-offs between alert quality and information latency. We see the value of distinguishing these tools as useful for highlighting and orienting users to choose to match the correct tool for an application; or to build a specialized Targeted Response tool when a Rapid Response tool does not meet their needs (Table 1).

Are CEAS Achieving Conservation Outcomes?

Measuring the conservation outcomes directly enabled by CEAS is difficult given the myriad of factors influencing environmental change, including global commodity demands, national and local politics, climate variations, land governance and socioeconomic factors. Rigorous evaluations may require specialized expertise and intense data collection to isolate the impact of a CEAS from confounding factors also influencing conservation outcomes. Assunção et al. (2017) provide an example of an impact evaluation of a CEAS used by law enforcement to reduce illegal environmental activities in Brazil by avoiding over 22,000 km^2 per year of deforestation. The analysis did not require intensive data collection as it used free and publicly available data on forest disturbance, cloud cover, and fines for illegal forest activities. The approach did require specialized expertise in impact evaluation to use an instrumental variables approach, a statistical technique used to determine a causal link between stricter law enforcement enabled by the INPE's CEAS, DETER and reduced deforestation from 2007 to 2011 (Assunção et al., 2017). INPE developed DETER in the mid-2000s, and the Brazilian Institute for Environmental and Renewable Natural Resources (Ibama), the government agency in charge of environmental law enforcement, quickly adopted the system to respond to illegal clearings. National support to reduce deforestation was essential to this successful application of CEAS. First, the government institution, INPE, had sufficient funding and technical capacity to build and operate DETER, second president Lula da Silva granted more legal support to Ibama to investigate and sanction environmental crimes; and third, Ibama recruited more talented personnel and provided advanced training for law enforcers. Since 2012, deforestation in the Brazilian Amazon has regained momentum, indicating the vulnerability of the national support for CEAS and environmental enforcement to national politics.

We see the value in impact evaluations of CEAS to quantify the cost savings of their societal benefits and encourage further research in this area. Fortunately, the demand for evidence-based conservation action over the past decade has prompted researchers and practitioners to publish better guidance on best practices for impact evaluation and involve more social science researchers in conservation work, for example, Blackman (2013) and Jones and Lewis (2015). While we acknowledge the current gap in knowledge of direct impacts, we recommend intermediate steps of designing better metrics to measure the *use* of CEAS for conservation decisions to help system developers improve CEAS without holding out for quantitatively rigorous evaluations.

Typically, CEAS developers measure system success using metrics related to system components (e.g., web site performance and design), data products (e.g., high resolution, low latency, data quality), and vanity metrics that indicate website popularity but (e.g., website visits, number of subscribers) with less emphasis on measuring the adoption of these systems by users and the outcomes they produce. We see an immediate opportunity to advance how we measure the impact of CEAS by designing better indicators to measure progress toward their uptake and use. In the remainder of this section, we provide a few examples of existing and potential indicators for CEAS.

In one example, Pratihast et al. (2016) developed monitoring indicators that measured progress toward improved forest management in the Kafa Bio-Sphere Reserve in Southwestern Ethiopia. Pratihast et al. (2016) measured improved forest management with proxy measures of increased conservation awareness, stakeholder participation, monitoring information accuracy and delivery, and increased enforcement activities. In another example, developing a metric to measure governmental agency alignment and coordination helped measure progress toward increased effectiveness. We suggest this potential indicator based on Finer et al.'s (2018) conclusion that reductions in deforestation occurred when governments implemented CEAS along with coordinated government agency efforts (e.g., in Brazil and Peru). Earlier, we highlighted the vulnerability of the DETER system when only used by a single type of stakeholder (e.g., national government agencies). Diversifying the user base may help maintain the use of the system for reducing deforestation when government support wanes. INPE and conservation organizations could increase access to CEAS and providing training to other stakeholders such as conservation practitioners, and IPLCs.

Learning from Humanitarian EWS

The most immediate action for CEAS system developers and conservation practitioners to increase the use of CEAS is to apply lessons learned from applications of humanitarian EWS, which have a long history of operation alerting to conflicts, disease outbreaks and natural disasters. From the literature of humanitarian EWS, we know that connecting information to a decision-maker who is empowered to act requires addressing the barriers to system use. We summarized these barriers to include access to the information, interpretability of the information, and trust in the information. Access to information has improved vastly with recent advances in technologies and social media. System operators leverage mobile technologies and social networks to disseminate information directly to those affected by threats and educate the public on preventative measures (Lwin et al., 2014). Accessible information must also be locally relevant, easy to interpret to make a decision, and must be sent within an appropriate timeframe to enable action (Macauley, 2006). Weak governance structures and lack of coordination between in-country institutions hinder information flow and reduce clarity and accountability for effective responses to warning information (Pulwarty and Sivakumar, 2014).

The lack of trust in data or systems, particularly in systems operated by foreign entities, is a multifaceted barrier to adoption (Pulwarty and Sivakumar, 2014; Stähli et al., 2015). Users may perceive EWS as surveillance technologies that reinforce power imbalances between the state and marginalized groups (Schintler and Kulkarni, 2014; Costa, 2017). Many systems operated from the US or Europe are designed to facilitate decision-making by stakeholders in the Global South (Schintler and Kulkarni, 2014) who are sometimes hesitant to rely on a system if they ultimately have no control over whether the system will be maintained or remains in operation (Kazansky et al., 2016). Additionally, there are concerns that monitoring technologies may place other types of knowledge systems (e.g., traditional ecological knowledge or TEK) or monitoring practices at risk, rather than bolstering or complementing such systems (Elwood, 2009; Young and Gilmore, 2017). To warrant trust in an EWS, both Sheffield et al. (2014) and Pulwarty and Sivakumar (2014) highlight the importance of collaboration with local partners as critical for overcoming poor adoption. Often government agencies may not adopt or endorse the use of these systems unless there is local ownership of the system and including local partners in the development and operation of EWS to reduce skepticism by users (Verdin et al., 2005; Pulwarty and Sivakumar, 2014; Stähli et al., 2015). Operators should also invest in a communications campaign about the advantage of using the system (e.g., what is in it for them) and how to use the system (Lwin et al., 2014). The communications campaign, outreach and engagement should aim for multi-sectorial involvement to enhance data sources and to facilitate information dissemination and engagement with diverse stakeholders (Kazansky et al. 2016).

Early in the development of humanitarian EWS, developers focused on improving information accuracy to support confident decision-making. With the recent advancement of monitoring technologies and computing, information accuracy from satellites is quite reliable. Further refinement of information accuracy aims to enhance the accuracy and spatial scale of satellite monitoring information by incorporating in-situ monitoring data and local knowledge sources (Verdin et al., 2005; Pulwarty and Sivakumar, 2014; Sheffield et al., 2014). Holistic

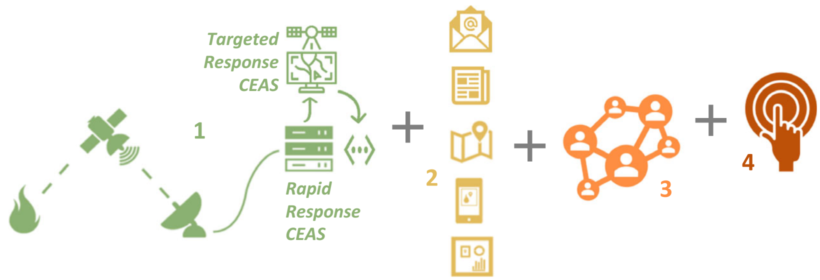

Figure 2. CEAS should connect a threat detection (1), and alert information (2), to a connected network of decision-makers (3) to enable a response (4). A Rapid Response CEAS typically uses NRT satellite monitoring to detect an ecosystem threat and processes and disseminates the information directly to a decision-maker. Targeted Response CEAS often enhance the information from Rapid Response CEAS with auxiliary information to produce higher quality data for targeted applications. CEAS alerts are communicated through a variety of media including email, social media, web maps, mobile apps, text alerts and dashboards. *Attribution: action icon by ahmad and satellite imagery icon by Template from the Noun Project.*

monitoring is another integrated approach that can produce more accurate predictive models by including socioeconomic, demographic, environmental and governance data (Kazansky et al. 2016).

Based on the experience of CEAS and humanitarian EWS operators, we recommend that a CEAS should link all components of an EWS outlined by Garcia and Fearnley (2012) including the information networks required to take action (Fig. 2) (Pulwarty and Sivakumar, 2014; Finer et al., 2018; Weisse et al., 2019). Furthermore, we highlight that none of the current CEAS address the sensitivities of introducing technology and the power imbalance between system developers, often from the developed world, to the users in the developing world; or between the state and marginalized populations; issues of concern to Elwood (2009), Costa (2017), and Young and Gilmore (2017). This topic, in particular, warrants further investigation given the recent focus of IPLC lands and their global significance for biodiversity conservation and climate mitigation (Garnett et al., 2018; Walker et al., 2020). Ultimately, overcoming barriers to adoption and use requires scrutinizing where CEAS are successful and where they are not, and making informed changes to these systems, the delivery of the information, and the engagement with the decision-maker/user.

Conclusion

CEAS can potentially play a critical role in supporting action and policies to work toward global sustainability goals. The shared vision of these systems is to provide transparency for global change, alert to emerging threats, and inform strategic and effective response. Despite the recent proliferation of systems, many of them have not been evaluated for the contribution to conservation outcomes. We recommend futher research to quantify how CEAS contribute to global goals of avoided emissions and achieving global sustainability targets, thus demonstrating their potential value. Given these evaluations can be expensive, time-intensive, and require a specialized skill set to perform, we reccomend research to design more targeted metrics to evaluate systems for achieving conservation outcomes. We can also look to long-established EWS for lessons learned on overcoming barriers to use. Addressing today's urgent conservation challenges requires linking accessible, trusted and effective CEAS to empowered people taking conservation actions.

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Data Availability Statement

N/A.

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