Opportunities for improving conservation early warning and alert systems

Karyn M. Tabor1,2 & Margaret B. Holland1

1Geography & Environmental Systems, University of Maryland Baltimore County, Baltimore, Maryland,
2Betty & Gordon Moore Center for Science, Conservation International, 2011 Crystal Drive, suite 600, Arlington Virginia,22202,

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   |
|--------------|-----------------------------------------------|-----------------------------------------------|-------------------|-----------------------|------------------------------------------------|--------------------|
| AFIS         | Advances Fire Information System (AFIS)        | Council for Scientific and Industrial         | South Africa      | Global                | Active fires, fire weather                      | RR                 |
| DETER        | Sistema de Detecção do Desmatamento em Tempo  | National Institute of Space Research (INPE)   | Brazil            | Brazil                | Forest disturbance                              | RR                 |
| EFFIS        | European Forest Fire Information System        | European Space Agency                         | European Union    | European Union        | Active fires                                    | RR                 |
| FAS          | Fire Alert System                              | Conservation International                    | USA               | Bolivia, Indonesia,   | Active fire                                    | RR                 |
| Firecast     | Fire and forest monitoring and alert system    | Conservation International                    | USA               | Bolivia, Colombia,    | Active fires, fire weather                      | RR                 |
| FIRMS        | Fire Information for Resource Management System| NASA                                          | USA               | Global                | Active fires                                    | RR                 |
| FORMA        | Forest Monitoring for Action                   | World Resource Institute                      | USA               | Global                | Forest disturbance                              | RR                 |
| Geobosques   | Geobosques                                    | Ministry of Environment (MINAM)               | Peru              | Peru                  | Forest disturbance                              | RR                 |
| GEOSERFOR    | GEOportal de la infraestructura de datos       | Ministerio de Agricultura y Riego             | Peru              | Peru                  | Active fires                                    | RR                 |
| GFW          | Global Forest Watch                            | The World Resource Institute                  | USA               | 20+ countries         | GLAD forest disturbance                        | RR                 |
| GFW Fires    | Global Forest Watch Fires                      | The World Resource Institute                  | USA               | Global                | Active fires, fire weather                      | RR                 |
| GFWED        | Global Fire Weather Database                   | NASA Goddard                                  | USA               | Global                | Fire weather                                    | RR                 |
| GLAD         | Global Land Analysis & Discover                | University of Maryland                        | USA               | 20+ countries         | Forest disturbance (30-m)                      | RR                 |
| GWIS         | Global Wildfire Information System             | Europeans Union’ Joint Research Centre       | European Union    | Global                | Active fires, fire weather                      | RR                 |
| JJ-FAST      | JICA-JAXA Forest Early Warning System in the   | JICA/JAXA                                     | Japan             | Global tropics        | Forest disturbance (50-m)                       | RR                 |
| MAAP         | Monitoring the Andean Amazon                   | Amazon Conservation                           | USA               | Bolivia, Brazil,     | Deforestation (<3 m)                           | TR                 |
| MAPBIOMAS    | MAPBIOMAS Alerta                               | MapBiomas                                     | Brazil            | Brazil                | Deforestation (<3-m)                           | TR                 |
| Mighty Earth | Mighty Earth Rapid Response Monitoring System  | Mighty Earth                                  | USA               | Indonesia, Malaysia, Ghana, Côte d’Ivoire | Deforestation, post-deforestation land use     | TR                 |

(Continued)
systems that emerged in the past decade, (e.g., Rey-mondin 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

| 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 Monterey 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 | Sentinel 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 | Active fires, fire weather, 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               | New Caledonia | Active fire, fire weather, burned area       |               |              |

2019-present RR

© 2020 The Authors. Remote Sensing in Ecology and Conservation published by John Wiley & Sons Ltd on behalf of Zoological Society of London
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 trade-offs 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 trade-offs 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
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 Sentinel 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 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 km² 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.
Improving Conservation Early Warning and Alert Systems

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
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 further 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 recommend 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.

**Acknowledgments**

The authors thank Dr. Dawn Biehler for her conceptual feedback and the reviewers for their exceptional guidance and suggested edits. This publication was made possible by the University of Maryland Graduate Student Association and a gift from Betty and Gordon Moore.

**References**

Assunção, J., C. Gandour, and R. Rocha. 2017. DETEr ring deforestation in the Brazilian Amazon: environmental monitoring and law enforcement..Climate Policy Initiative. Rio de Janeiro, Brazil, 1–36.

Blackman, A. 2013. Evaluating forest conservation policies in developing countries using remote sensing data: an introduction and practical guide. Forest Policy Econ. 34, 1–16. https://doi.org/10.1016/j.forpol.2013.04.006

Costa, L. M. 2017. En foco: Ambiente, Sociedad y Comunicación. Cuaderno Venezolano de Sociología 26, 83–97.

Crouzeilles, R., R. Feltran-Barbieri, M. S. Ferreira, and B. B. N. Strassburg. 2017. Hard times for the Brazilian environment. Nat Ecol Evol. 1, 1213–1213, https://doi.org/10.1038/s41559-017-0303-7

Davies, D. K., S. Ilavajhala, M. M. Wong, and C. O. Justice. 2009. Fire information for resource management system:
archiving and distributing MODIS active fire data. *IEEE Trans. Geosci. Remote Sens.* **47**, 72–79. https://doi.org/10.1109/TGRS.2008.2002076

Davies, D. K., M. E. Brown, K. J. Murphy, K. A. Michael, B. T. Zavodskey, E. N. Stavros, et al. 2017. Workshop on using NASA data for time-sensitive applications. *IEEE Geosci Remote Sens Magazine* **5**(3) 52–58, https://doi.org/10.1109/MGRS.2017.2729278.

De Sy, V., M. Herold, C. Martius, H. Böttcher, S. Fritz, D. Gaveau, et al. 2016. *Enhancing transparency in the land-use sector: exploring the role of independent monitoring approaches*. Center for International Forestry Research, Bogor, Indonesia. https://doi.org/10.17528/cifor/006256

Diniz, C. G., A. A. D. A. Souza, D. C. Santos, M. C. Dias, N. C. Da Luz, D. R. V. De Moraes, et al. 2015. DETER-B: the new Amazon near-real-time deforestation detection system. *IEEE J. Select. Topics Appl. Earth Obs. Remote Sens.* **8**, 3619–3628. https://doi.org/10.1109/JSTARS.2015.2437075

Elwood, S. 2009. Thinking outside the box: engaging critical geographic information systems theory, practice and politics in human geography. *Geogr. Compass* **4**, 45–60. Retrieved from http://onlinelibrary.wiley.com/doi/10.1111/j.1749-8198.2009.00289.x/full.

FAO. 2018. *REDD+ reducing emissions from deforestation and forest degradation*. United Nations Food and Agriculture Organization, Rome, Italy. Retrieved from http://www.fao.org/redd/news/detail/en/c/1149406/.

Fearnside, P. M. 2010. Deforestation of the Brazilian Amazon (Vol. 1). https://doi.org/10.1093/acrefore/9780199389414.013.102

Finner, M., S. Novoa, M. J. Weisse, R. Petersen, J. Mascaro, T. Souto, et al. 2018. Combating deforestation: from satellite to intervention. *Science* **360**, 1303–1305. https://doi.org/10.1126/science.aat1203

Garcia, C., and C. J. Fearnley. 2012. Evaluating critical links in early warning systems for natural hazards. *Environ. Hazards* **11**, 123–137. https://doi.org/10.1080/17477891.2011.698877

Garnett, S. T., N. D. Burgess, J. E. Fa, Á. Fernández-Llamazares, Z. Molnár, C. J. Robinson, et al. 2018. A spatial overview of the global importance of Indigenous lands for conservation. *Nat. Sustain.* **1**, 369–374. https://doi.org/10.1038/s41893-018-0100-6

Hansen, M. C., P. V. Potapov, R. Moore, M. Hancher, S. Turubanova, A. Tyukavina, et al. 2013. High-resolution global maps of 21st-century forest cover change. *Science (New York, N.Y.)* **342**, 850–853. https://doi.org/10.1126/science.1244693

Hansen, M. C., A. Krylov, A. Tyukavina, P. V. Potapov, S. Turubanova, B. Zutta, et al. 2016. Humid tropical forest disturbance alerts using Landsat data Humid tropical forest disturbance alerts using Landsat data. *Environ. Res. Lett.* **11**, 034008. https://doi.org/10.1088/1748-9326/11/3/034008

Jones, K. W., and D. J. Lewis. 2015. Estimating the counterfactual impact of conservation programs on land cover outcomes: the role of matching and panel regression techniques. *PLoS One* **10**, 1–22. https://doi.org/10.1371/journal.pone.0141380

Justice, C., L. Giglio, S. Korontzi, J. Owens, J. T. Morisette, D. Roy, et al. 2002. The MODIS fire products. *Remote Sens. Environ.* **83**, 244–262. https://doi.org/10.1016/S0034-4257(02)00076-7

Kazansky, Y., D. Wood, and J. Sutherland. 2016. The current and potential role of satellite remote sensing in the campaign against malaria. *Acta Astronaut.* **121**, 292–305. https://doi.org/10.1016/j.actaastro.2015.09.021

Laurance, W. F., F. Achard, S. Peedell, and S. Schmitt. 2016. Big data, big opportunities. *Front. Ecol. Environ.* **14**, 347. https://doi.org/10.1002/fee.1316

Lwin, M. O., S. Vijaykumar, O. Fernando, N. Newton, S. A. Cheong, V. S. Rathnayake, et al. 2014. A 21st century approach to tackling dengue: crowdsourced surveillance, predictive mapping and tailored communication. *Acta Trop.* **130**, 100–107.

Lynch, J., M. Maslin, H. Balzter, and M. Sweeting. 2013. Sustainability: choose satellites to monitor deforestation. *Nature* **496**, 293–294. https://doi.org/10.1038/496293a

Macauley, M. K. 2006. The value of information: measuring the contribution of space-derived earth science data to resource management. *Space Policy* **22**(4), 274–282. https://doi.org/10.1016/j.spacepol.2006.08.003

Musinsky, J. 2014. Near-real time monitoring and alert systems. Pp. 181–199 in J. Hewson, M. Steininger, and S. Pesmajoglou, eds. *REDD+ measurement, reporting and verification (MRV) manual, version 2.0*. Forest Carbon, Markets and Communities (FCMC) Program, Washington, DC.

Musinsky, J., K. Tabor, C. A. Cano, J. C. Ledezma, E. Mendoza, A. Rasolohery, et al. 2018. Conservation impacts of a near real-time forest monitoring and alert system for the tropics. *Remote Sens. Ecol. Conserv.* **4**, 189–196. https://doi.org/10.1002/rse2.78

Palomino, J., O. C. Muellerklein, and M. Kelly. 2017. A review of the emergent ecosystem of collaborative geospatial tools for addressing environmental challenges. *Comput. Environ. Urban Syst.* **65**, 79–92. https://doi.org/10.1016/j.compeurb.2017.05.003

Potter, C. 2014. Global assessment of damage to coastal ecosystem vegetation from tropical storms. *Remote Sensing Letters* **5**(4), 315–322. https://doi.org/10.1080/2150704X.2014.902546

Pratihast, A. K., B. DeVries, V. Avitabile, S. van Bruin, M. Herold, and A. Bergsma. 2016. Design and implementation of an interactive web-based near real-time forest monitoring system. *PLoS One* **11**(3), e0150935. https://doi.org/10.1371/journal.pone.0150935

Pulwarty, R. S., and M. V. K. Sivakumar. 2014. Information systems in a changing climate: early warnings and drought risk management. *Weather Clim. Extremes* **3**, 14–21. https://doi.org/10.1016/j.wace.2014.03.005
Reiche, J., R. Verhoeven, J. Verbeselt, E. Hamunyela, N. Wielaard, and M. Herold. 2018. Characterizing tropical forest cover loss using dense Sentinel-1 data and active fire alerts. Remote Sens. 10(5), 1–18. https://doi.org/10.3390/rs10050777

Reymondin, L., K. Argote, A. Jarvis, C. Navarrete, A. Coca, D. Grossman, et al. 2013. Monitoring land-use change in Latin America: results of five case road impact assessment using remote sensing methodology for monitoring land-use change in Latin America: results of Five Case Studies, (July 2013), 31.

Schintler, L. A., and R. Kulkarni. 2014. Big data for policy analysis: the good, the bad, and the ugly. The Review of Policy Research 31(4), 343–348. https://doi.org/10.1111/ropr.12079

Schroeder, W., and L. Giglio. (2018). NASA VIIRS Land Science Investigator Processing System (SIPS) Visible Infrared Imaging Radiometer Suite (VIIRS) 375 m & 750 m Active Fire Products: product User’s Guide Version 1.4. Retrieved from https://landweb.modaps.eosdis.nasa.gov/NPP/forPage/NPPguide/VIIRS_Active_Fire_User_Guide_v1.4.pdf.

Sheffield, J., E. F. Wood, N. Chaney, K. Guan, S. Sadri, X. Yuan, et al. 2014. A drought monitoring and forecasting system for sub-Saharan African water resources and food security. Bull. Am. Meteor. Soc. 95, 861–882. https://doi.org/10.1175/BAMS-D-12-00124.1

Shimabukuro, Y. E., J. R. dos Santos, A. R. Formaggio, V. Duarte, and B. F. T. Rudorff. 2013. The Brazilian Amazon monitoring program: PRODES and DETER projects. Pp. 354 in F. Achard, and M. C. Hansen, eds. Global forest monitoring from earth observation. CRC Press, Boca Raton, FL.

Stähli, M., M. Sättele, C. Huggel, B. W. McArdell, P. Lehmann, A. Van Herwijnen, et al. 2015. Monitoring and prediction in early warning systems for rapid mass movements. Nat. Hazards Earth Syst. Sci. 15, 905–917. https://doi.org/10.5194/nhess-15-905-2015

Tabor, K., and J. Hewson.2018. The evolution of remote sensing applications vital to effective biodiversity conservation and sustainable development, Chapter 9. Pp. 274-300 in G. M. Buchanan and A. K. Leidner, eds. Satellite remote sensing for conservation action: case studies of implementation. Cambridge University Press, Cambridge, UK.

Verdin, J., C. Funk, G. Senay, and R. Choularton. 2005. Climate science and famine early warning. Philos. Trans. R. Soc. B: Biol. Sci. 360, 2155–2168. https://doi.org/10.1098/rstb.2005.1754

Walker, W. S., S. R. Gorelik, A. Baccini, J. L. Aragon-Osejo, C. Josse, C. Meyer, et al. 2020. The role of forest conversion, degradation, and disturbance in the carbon dynamics of Amazon indigenous territories and protected areas. Proc. Natl. Acad. Sci. 117, 3015–3025. https://doi.org/10.1073/pnas.1913321117.

Weisse, M. J., R. Noguerón, R. Eduardo, V. Vicencio, D. Arturo, and C. Soto. 2019. Use of near-real-time deforestation alerts: a case study from Peru. World Resources Institute, Washington, D.C.

Wheeler, D., D. Hammer, R. Kraft, and A. Steele. 2014. Satellite-based forest clearing detection in the brazilian Amazon: FORMA, DETER, and PRODES In. World Resources Institute Issue Brief, 1–24.

Whittall, J. 2010. Humanitarian early warning systems: myth and reality. Third World Q. 31, 1237–1250. https://doi.org/10.1080/01436597.2010.542967

Young, J., and M. Gilmore. 2017. Participatory uses of geospatial technologies to leverage multiple knowledge systems within development contexts: a case study from the peruvian Amazon. World Dev. 93, 389–401. https://doi.org/10.1016/j.worlddev.2017.01.007