Remote Monitoring Systems for Conservation of the Amazon Rainforest: A Systematic Review

Sistemas de monitoreo remoto para la conservación del bosque tropical húmedo amazónico: una revisión sistemática

Sistemas de monitorização remota para a conservação da floresta amazónica: Uma revisão sistemática

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Abstract

The Amazon rainforest plays a crucial role in stabilizing the global climate and is vital for preserving biodiversity, wildlife, and indigenous cultures. Despite efforts to protect the Amazon rainforest, deforestation, wildlife trafficking, mining, oil exploitation and other extractive industries continue to threaten the region. Remote Monitoring Systems (RMS) are necessary to effectively detect and analyze these threats. This systematic review of technological initiatives to protect natural resources demonstrates the importance of technology in conservation and the need for further research

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and development. This article identifies technologies used worldwide for conservation efforts and highlights the challenges in developing an RMS for the Amazon region, such as harsh environmental conditions and limited infrastructure. The timely detection of threats could help authorities take corrective actions and prevent further environmental effects on the Amazon rainforest.

Keywords: Tropical rainforest, sensor, biodiversity protection

Resumen

El bosque tropical húmedo amazónico desempeña un papel crucial en la estabilización del clima mundial y es vital para preservar la biodiversidad, la vida salvaje y las culturas indígenas. A pesar de los esfuerzos por proteger la Amazonia; la deforestación, el tráfico de especies silvestres, la minería, la explotación petrolera y otras industrias extractivas siguen amenazando la región. Los sistemas de monitoreo remoto (RMS) son necesarios para detectar y vigilar eficazmente estas amenazas. Esta revisión sistemática de las iniciativas tecnológicas para proteger los recursos naturales demuestra la importancia de la tecnología en la conservación y la necesidad de seguir investigando y desarrollando en dichas tecnologías. En este artículo se identifican los tipos de tecnologías utilizadas en los distintos continentes y se destacan los retos que plantea el desarrollo de un RMS para la Amazonia, entre los que se incluyen las duras condiciones ambientales y las limitadas infraestructuras. La detección a tiempo de las amenazas podría ayudar a las autoridades a tomar medidas correctivas y evitar una mayor afectación medioambiental del bosque amazónico.

Palabras clave: Bosque tropical, sensor, protección de la biodiversidad

Resumo

A floresta tropical amazónica desempenha um papel crucial na estabilização do clima global e é vital para a preservação da biodiversidade, da vida selvagem e das culturas indígenas. Apesar dos esforços para proteger a Amazónia, a desflorestação, o tráfico de animais selvagens, a mineração, a exploração petrolífera e outras indústrias extrativas continuam a ameaçar a região. São necessários sistemas de monitorização remota (RMS) para detectar e monitorizar eficazmente estas ameaças. Esta revisão sistemática das iniciativas tecnológicas para proteger os recursos naturais demonstra a importância da tecnologia na conservação e a necessidade de mais investigação e desenvolvimento. Este artigo identifica os tipos de tecnologias utilizadas em diferentes continentes e destaca os desafios do desenvolvimento de um RMS para a Amazónia, incluindo condições ambientais adversas e infraestruturas limitadas. A deteção precoce de ameaças pode ajudar as autoridades a tomar medidas corretivas e a evitar mais danos ambientais na floresta amazónica.

Palavras-chave: Floresta tropical, sensor, proteção da biodiversidade

Introduction

The Amazon rainforest, the largest forest in the world, spans a significant portion of Brazil and Peru, along with parts of Guyana, Colombia, Ecuador, Bolivia, Suriname, French Guiana, and Venezuela. The Amazon River Basin is the world's largest drainage system and sustains the biggest rainforest on the planet, accounting for over half of the total volume of rainforests globally. It serves as a vital water reserve for humanity. In Colombia, for example, the Amazon rainforest encompasses 36% of the national territory (Oliveira and Figueira, 2021; Plotkin, 2020).

The Amazon is characterized by a tropical forest biome, featuring dense vegetation, rugged terrain, and a hot, humid climate (Gobernación de Amazonas, 2020). The Amazon rainforest plays a crucial role in the carbon cycle, helping to stabilize the global climate. It is estimated (Plotkin, 2020) that the Amazon contains one-fifth of all the planet's terrestrial carbon. Without this forest, carbon would be released into the atmosphere, worsening climate change. The Amazon rainforest functions as both a sponge and a gutter, absorbing abundant rainfall and releasing moisture back into the atmosphere through transpiration. Researchers at the University of Leeds assert that deforestation not only diminishes local rainfall but can also directly lead to droughts (Spracklen and Garcia-Carreras, 2015).

Protected areas and Indigenous reserves are crucial for rainforest conservation, particularly in the Amazon rainforest, which is home to several large national parks. One notable example is the Parque Nacional Natural Río Puré in Colombia, which spans approximately 10,000 km^2. This area is comparable in size to the urban area of New York City, which covers about 12,000 km^2 (Ministerio del Medio Ambiente, República de Colombia, 2002).

Additionally, both Chiribiquete (43,000 km^2) in Colombia and Tumucumaque (38,874 km^2) in Brazil exceed the size of Belgium (30,688 km^2) (Plotkin, 2020). This underscores the considerable extent of these protected areas. Despite efforts to implement and adopt protective measures, the Amazonian territory remains plagued by issues such as drug trafficking, armed conflict, wildlife trafficking, illegal mining, selective logging, deforestation for agriculture and livestock, and oil exploitation (Figueira et al., 2015; 2020; Moutinho, 2021; Oliveira and Figueira, 2021). Furthermore, since larger national parks are often situated in remote areas far from urban centers, they can be challenging to monitor and safeguard (Plotkin, 2020). As threats to the Amazon Rainforest continue to escalate, it is increasingly essential to develop Remote Monitoring Systems (RMS) capable of effectively detecting and surveying these threats in protected regions.

The protection of the Amazon is critically tied to multiple UN (United Nations) sustainable development goals, as its preservation is essential for mitigating climate change while ensuring the conservation of the region's biodiversity (United Nations, 2023e). Specifically, the protection of the Amazon is associated with the following UN sustainability goals:

Goal 13: Climate Action - The Amazon serves as a major carbon sink, and its preservation is necessary for mitigating climate change (Collen, 2016; Painter et al., 2022; United Nations, 2023a).

Goal 14: Life Below Water - The Amazon is linked to numerous rivers and aquatic systems, making its protection vital for preserving marine life (Collen, 2016; Painter et al., 2022; United Nations, 2023b).

Goal 15: Life On Land - The Amazon is one of the most biodiverse regions globally, and conserving its terrestrial ecosystem is crucial for preserving wildlife and biodiversity (Collen, 2016; Painter et al., 2022; United Nations, 2023c).

Goal 16: Peace, Justice, and Strong Institutions - The protection of the Amazon is also fundamentally linked to promoting environmental justice and safeguarding the rights of indigenous peoples in the region (Collen, 2016; Painter et al., 2022; United Nations, 2023d).

To emphasize the significance of specific technologies as vital tools for the protection and conservation of the Amazon rainforest, this article reviews various initiatives aimed at preserving biodiversity across different ecosystems worldwide. The systematic review utilized the Scopus and IEEE Xplore databases, employing the keywords “amazon,” “rainforest,” “remote,” and “monitoring,” while refining results to focus on engineering and sciences. From an initial pool of 216 articles, a thorough two-stage screening process reduced the selection to 92, which were examined for key information such as implementation location, system components, and technologies. This serves as a valuable guide for proposing new initiatives and promotes the exploration of fresh perspectives.

This document is structured as follows: Section two presents various tropical rainforest monitoring systems, while section three outlines the requirements for a Remote Monitoring System, taking into account the characteristics of the Amazon rainforest. Lastly, the conclusions section offers some final considerations.

Remote Monitoring Systems Worldwide

Several initiatives have been implemented globally to preserve natural resources. These strategies are generally aimed at achieving one or more of the following actions: detecting intruders, apprehending illegal poachers, and assessing the integrity or forest cover of protected areas. The use of technology plays a crucial role in the conservation and sustainability of ecosystems. In particular, applying sensing technologies (Kamminga et al., 2018) has proven effective in gathering data that helps authorities mitigate potential threats more efficiently.

Some of the technological initiatives proposed and implemented worldwide to protect natural resources are presented in Tables 1 to 4. Table 1 summarizes the remote monitoring systems implemented in Asia, Table 2 in Europe, Table 3 in Africa, and Table 4 in America. The four tables:

- Group the initiatives by continent.
- Present the year of proposal and/or implementation.
- Indicate the country of implementation.
- Identify the institutions and entities involved in the initiative.

- Establish the objective of the initiative, such as controlling deforestation, protecting against illegal logging, or combating poaching, among others.
- Specify the type of technology proposed and/or implemented.
- Include a reference.
- Indicate its location on the map in Figure 3 with an item.

Table 1 below presents the remote monitoring initiatives that have been proposed and/or implemented on the Asian continent.

Table 1. Remote monitoring systems implemented in Asia

Year	Country	Institution	Objective	Technology	Reference/Name	Item
2012	Indonesia	RSS-Remote Sensing Solutions GmbH (Germany)	Detect illegal logging	Treatment and processing of satellite images	(Franke et al., 2012)	1
2017	Taiwan	Chaoyang University of Technology	Detect illegal logging	Gravity sensor Acoustic sensor Cameras	(Chen and Liaw, 2017)	2,3
2017	Sri Lanka	Sri Lanka Institute of Information Technology	Detect illegal logging	Acoustic sensor	(Kalhara et al., 2017) TreeSpirit	4
2018	India	Indian Institute of Information Technology	Detect illegal logging	Acoustic sensor	(Sharma, 2018)	5
2018	Indonesia	Telkom University	Detect illegal logging	Acoustic sensor Vibration sensor	(Prasetyo et al., 2018)	6
2020	Indonesia	Telkom University	Detect illegal logging	Acoustic sensor Vibration sensor	(Mutiara, Herman, et al., 2020; Mutiara, Suryana, et al., 2020)	7,8
2020	Thailand	University Bangkok, Mahidol University	Detect illegal logging	Acoustic sensor Vibration sensor	(Srisuphab et al., 2020)	9
2020	Thailand	Princess Chulabhorn Science High School	Detect chainsaw logging	Acoustic sensor	(Jubjainai et al., 2020)	10
2020	Philippines	Adamson University	Detect illegal logging and poaching	Acoustic sensor	(Arevalo et al., 2020) SENTRY	11
2020	Saudi Arabia	University of Ha'il	Detect illegal logging and poaching	Acoustic sensor Vibration sensor	(Yadav, 2020)	12
2020	India	Mepco Schlenk Engineering College	Monitor deforestation	Vibration sensor Flame sensor Tilt sensor	(Sivasankari and Mounika, 2020)	13

2021	Malaysia	University Technology MARA	Monitor illegal logging	Airborne LiDAR sensor Treatment and processing of satellite images	(Rozali, 2021)	14
2021	India	Dayananda Sagar University	Anti-poaching and fire alarm System	Temperature sensor Smoke sensor (LDR) Light Dependent Resistor sensor	(Ishitha et al., 2021)	15
2021	India	Pimpri Chinchwad College of Engineering	Anti-Poaching deforestation alarm system	Vibration sensor Fire sensor Tilt sensor	(Chhabra et al., 2021)	16
2022	India	SCAD College of Engineering and Technology	Monitor deforestation	Acoustic sensor	(Kumar et al., 2022)	17
2022	India	Department of Computer Science and Engineering. BBD University.	Monitor deforestation	Vibration sensor	(Ahmad and Singh, 2022)	18
2022	Sri Lanka	Institute of Information Technology (SLIIT)	Detect forest fire	Acoustic sensor	(Bandaranayake et al., 2022)	19
2022	Sri Lanka	General Sir John Kotelawala Defence University	Detect illegal logging	Humidity sensor Gas sensor (CO2) (LDR) Light Dependent Resistor sensor	(Dampage et al., 2022)	20
2022	Bangladesh	University of Queensland (Australia). Shahjalal University of Science and Technology (Bangladesh)	Detect illegal logging	Treatment and processing of satellite images	(Redowan et al., 2022)	21
2023	Indonesia	Forest Harvesting Laboratory, Faculty of Forestry, Hasanuddin University	Monitor illegal logging using Google Earth	Treatment and processing of satellite images	(Mujetahid et al., 2023)	22
2023	India	Hindustan Institute of Technology and Science, Karunya Institute of Technology, Sciences, Coimbatore	Monitor illegal logging	Tilt sensor Fire sensor Smoke sensor Acoustic sensor	(Kameswararao et al., 2023)	23

2023	India	IFET College of Engineering	Monitor illegal logging, deforestation, trafficking, and poaching	Cameras (RFID) Radio Frequency Identification (PIR) Passive Infrared Sensor	(Arunkumar and Raj, 2023)	24
2023	India	Uttaranchal University, Dehradun, Meerut Institute of Technology, D.S.B Campus Kumaun University, Universidad Internacional Iberoamericana (México)	Monitor illegal poaching	Cameras	(Singh et al., 2023)	25

When analyzing the solutions presented in Table 1, which includes Asian-led initiatives aimed at protecting biodiverse territories from threats such as deforestation, illegal poaching, logging, and deliberate acts of arson, it is evident, as illustrated in Figure 1, that the majority of the proposals (27%) focus on the implementation of acoustic sensors, followed by vibration sensors (17%). Acoustic sensors offer a significant advantage in detecting sounds over long distances, making them valuable for monitoring events across large areas. However, they also have drawbacks, as they can be considerably influenced by complex environmental conditions and background noise, which may distort measurement results (Iniewski, 2017; Kamminga et al., 2018; Webster, 1999).

On the other hand, Europe has spearheaded several initiatives aimed at remote monitoring of wildlife, environmental measurements, and the detection of illegal logging. The solutions outlined in Table 2 utilize LiDAR technology, which is widely employed for precise measurement of distance, height, and shape of objects and surfaces. However, its primary drawback is that its detection capability can be hindered by the density of foliage and trees in the environment (Comstock et al., 2002; Dubayah and Drake, 2000; Lim et al., 2003; Schwarz, 2010). In addition to LiDAR, other solutions have incorporated acoustic and magnetic sensors, which provide high accuracy and sensitivity for tracking wildlife movements. Nonetheless, it is crucial to acknowledge that these sensors have limitations in detecting non-magnetic materials, and their application is primarily confined to short-distance measurements (Kamminga et al., 2018).

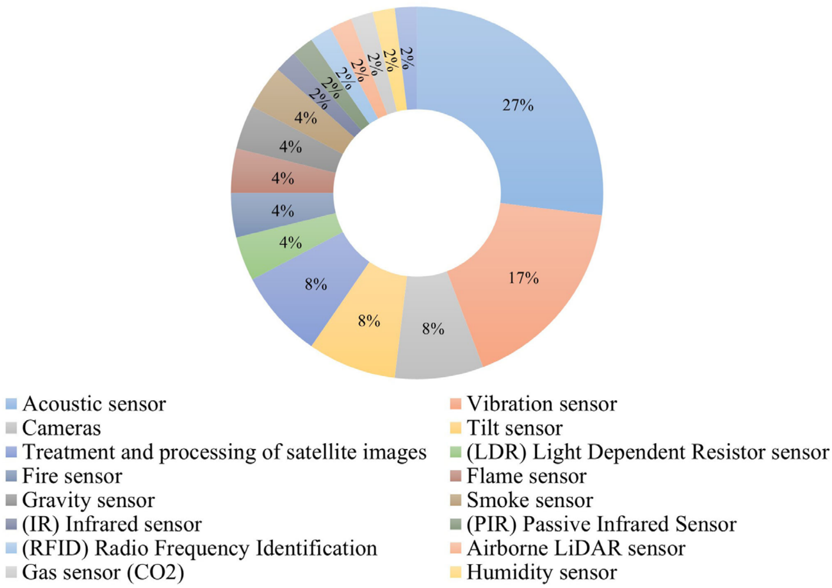

Figure 1. Technologies Utilized in Remote Monitoring Systems Across the Asian Continent.

Table 2. Remote monitoring systems implemented in Europe

Year	Country	Institution	Objective	Technology	Reference/Name	Item
2013 2018	United Kingdom	Zoological Society of London (ZSL), Cambridge Consultants, Iridium, Seven Technologies Group, Wireless Innovation	Remotely monitor wildlife	Magnetic sensor Cameras	(Amin et al., 2017; Brittain, 2018; Ovienmhada, 2015; Seccombe, 2019; Wireless Innovation, 2016; Zoological Society of London, 2013) Instant Detect 2.0	26-31
2018	Romania	University Politehnica of Bucharest	Detect illegal logging	Acoustic sensor	(Gaiţă et al., 2018)	32
2020	United Kingdom	University of Hertfordshire	Detect illegal logging	Acoustic sensor	(Mporas et al., 2020)	33
2022	Romania	University Bucharest	Detect illegal logging and measurement environmental parameters	LiDAR (Light Detection and Ranging) Acoustic sensor	(Oancea et al., 2022)	34
2022	Romania	University Bucharest	Monitor illegal logging, poaching	LiDAR (Light Detection and Ranging)	(Coman et al., 2022)	35
2023	Romania	Rainforest Connection, Huawei	Monitor illegal logging, poaching	Acoustic sensor	(Rainforest Connection, 2023) Guardian	36

Table 3 presents several proposals aimed at protecting and conserving biodiversity across the African continent, with the goal of preventing the illegal poaching of endangered wildlife. These solutions primarily utilize radar-type sensors, which offer the advantage of high accuracy in detecting and measuring objects over long distances, even under adverse weather conditions. However, their implementation can be costly, and they may be susceptible to electromagnetic interference (Skolnik, 2001; 2008). Additional solutions that have been employed include cameras, as well as optical and acoustic sensors.

Table 3. Remote monitoring systems implemented in Africa

Year	Country	Institution	Objective	Technology	Reference/Name	Item
2014	Madagascar	Center for Sustainability at Saint Louis University (USA)	Protection and conservation of biodiversity	(InSAR) Interferometric Synthetic Aperture Radar	(Ghulam, 2014)	37
2015	South Africa	Cisco Systems and Dimension Data	Anti-poaching in the Kruger National Park	Cameras Thermal sensor	(Cisco Systems, 2019; Connected Conservation Foundation, 2022; Dimention Data, 2019; Neme, 2018) Connected Conservation	38-41
2016	South Africa	South African National Parks (SANParks), Peace Parks Foundation and the Council for Scientific and Industrial Research of South Africa (CSIR)	Anti-poaching in the Kruger National Park	Radar (radio detection and ranging) Optical sensor Cameras	(Foundation Peace Parks, 2018; Reutech Radar Systems, 2017; South Africa's Council for Scientific And Industrial Research (CSIR), 2016) Postcode Meerkat Postcode Meerkat	42-44
2023	Cameroon, South Africa	Rainforest Connection, Huawei	Detect illegal logging and poaching	Acoustic sensor	(Rainforest Connection, 2023) Guardian	45

Table 4 presents various alternatives in America for protecting the Amazon rainforests. Figure 2 indicates that these initiatives focus on monitoring deforestation through satellite image processing and analysis, which accounts for 41% of the proposed solutions. Additionally, cameras (15%) and acoustic sensors (11%), typically in the form of camera traps, have been employed in various designs to collect data on Amazonian biodiversity. Among the initiatives presented, the use of satellite monitoring systems and mission-oriented sensor systems stands out as the primary methods for rainforest monitoring.

Table 4. Remote monitoring systems implemented in the Americas

Year	Country	Institution	Objective	Technology	Reference/Name	Item
2013	Ecuador	College of Biological and Environmental Sciences, Universidad San Francisco de Quito	Monitor illegal deforestation	(IR) Infrared sensor Cameras	(Jaramillo, 2013)	46
2015	Brazil	National Institute for Space Research-INPE, Parque de Ciencia de Tecnología do Guama	Detect deforestation	Treatment and processing of satellite images	(Diniz et al., 2015) DETER-B	47
2015 2017	Perú	Pontificia Universidad Católica de Perú	Protection and conservation of biodiversity	(PIR) Passive Infrared Sensor CMOS camera	Camacho et al., 2017; TAPIRnet/ Tapirduino	48
2016	Brazil	University of Amazonas	Protect environment and detect illegal logging in the Amazon rainforest	Acoustic sensor	(Colonna et al., 2016)	49
2018	Brazil	Mamirauá Institute, The Sense of Silence Foundation, Polytechnic University of Catalonia (Spain)	Protection and conservation of biodiversity	Acoustic sensor Cameras	(Sierra Praeli, 2018) Proyecto Providence	50
2018	Bolivia	Wageningen University and Research, The Netherlands	Real-time deforestation monitoring	Treatment and processing of satellite images (SAR) Synthetic Aperture Radar	(Reiche et al., 2018) RADD	51
2019	Brazil	National Institute for Space Research (INPE)	Detect deforestation	Treatment and processing of satellite images	(Shimabukuro et al., 2019)	52
2019	Guatemala	Deimos Space UK Ltd	Detect deforestation	Treatment and processing of satellite images	(Wyniawskyj et al., 2019)	53
2020	Perú	Joanneum Research Forschungsgesells chaft mbH, Austria	Forest monitoring	Treatment and processing of satellite images (SAR) Synthetic Aperture Radar	(Hirschmugl et al., 2020)	54

2021	Brazil	National Institute for Space Research (INPE)	Detect deforestation	Treatment and processing of satellite images	(Moutinho, 2021) Amazonia-1	55
2021	United States	Embry-Riddle Aeronautical University, California State University Chico	Detect poaching	Accelerometer sensor Geophone sensor Camera trap Treatment and processing of satellite images	(Dorfling et al., 2021)	56
2022	Brazil	Universidade de Brasília, Brazilian Agricultural Research Corporation (EMBRAPA), University of Rome "Tor Vergata" (Italy)	Detect deforestation	Treatment and processing of satellite images	(Silva et al., 2022)	57
2022	Perú	Chiba University (Japan)	Detect deforestation	Treatment and processing of satellite images	(silva, 2022)	58
2022	Brazil	National Institute for Space Research (INPE), Brazil	Forest disturbance detection	Treatment and processing of satellite images (SAR) Synthetic Aperture Radar	(Doblas et al., 2022) DETER-R	59
2023	United States, Costa Rica, Ecuador, Perú, Bolivia, Colombia, Brazil	Rainforest Connection, Huawei	Detect illegal logging and poaching	Acoustic sensor	(Rainforest Connection, 2023) Guardian	60
2023	Brazil	Rio de Janeiro State University	Detect deforestation	Treatment and processing of satellite images	(de Andrade et al., 2022)	61
2023	Colombia	Universidad Nacional de Colombia	Protection and conservation of biodiversity	Radar (radio detection and ranging) Camera	(Torres et al., 2023)	62

Satellite monitoring systems utilize satellites orbiting the Earth to gather data on specific areas of interest, including information regarding forest health, such as changes in vegetation cover or deforestation. The advantage of satellite monitoring lies in its capacity to cover large areas swiftly and efficiently, offering a comprehensive overview of the rainforest's condition (Bragilevsky and Bajić, 2017; Ghulam, 2014; Krasovskii et al., 2018). However, the effectiveness of satellite monitoring is contingent upon the spatial resolution of the system. Higher resolution enables the detection of low-intensity logging, but continuous imaging is necessary due to climatological factors, such as rapidly changing cloud cover in the humid rainforest environment. Furthermore, temporal resolution is vital not only because of these climatological factors but also due to the rapid regrowth of vegetation in the rainforest, which can quickly obscure the impacts of logging (Franke et al., 2012). Satellite monitoring has its limitations. Satellites can only provide data on what they can observe, meaning they may overlook significant changes or events occurring beneath the forest canopy. Additionally, satellite data may not offer detailed real-time information about the specific causes of changes, such as whether deforestation results from human activity or natural events (Arevalo et al., 2020). Various approaches have combined the use of Synthetic Aperture Radars (SAR) with images obtained from optical satellites to enhance the detection of deforestation in areas with frequent cloud cover (Doblas et al., 2022; Hirschmugl et al., 2020; Reiche et al., 2018). These systems have demonstrated increased accuracy in detection following human validation.

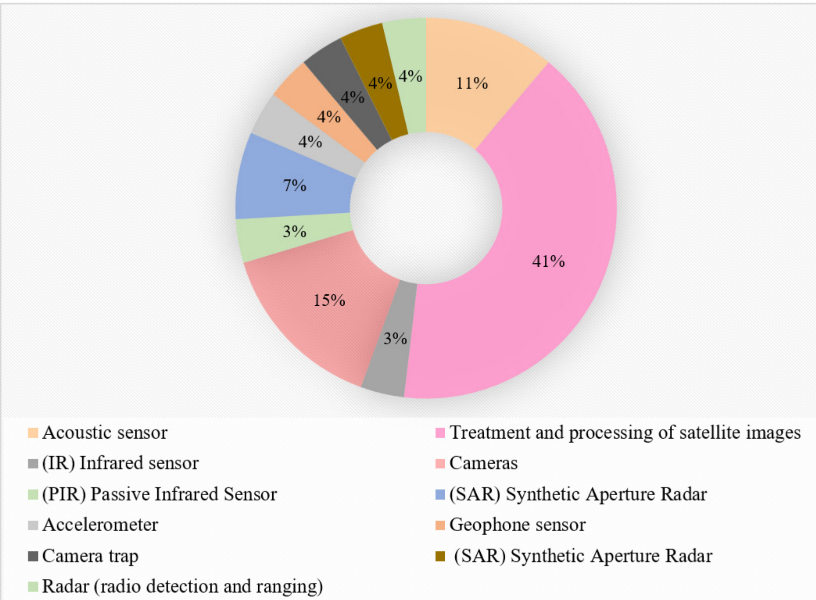

Figure 2. Technologies Utilized in Proposed Remote Monitoring Systems in the Americas

Mission-oriented sensor systems, on the other hand, can be specifically designed to monitor and protect the tropical rainforest. These sensors include Airborne Lidar (Light Detection and Ranging), Airborne SAR (Synthetic Aperture Radar), thermal cameras, microphones, RGB cameras, high-precision Global Positioning System (GPS) receivers, Inertial Measurement Units (IMU), and other devices strategically placed throughout the forest. They collect detailed information about specific areas, such as the presence of endangered species or illegal logging activities (Ammari, 2019; Figueira et al., 2015).

One advantage of mission-oriented sensors is their ability to deliver highly detailed information about specific areas of interest. This capability can be particularly beneficial for identifying and tracking illegal activities in the rainforest. Furthermore, mission-oriented sensors can be designed for autonomous operation, allowing them to function for extended periods without human intervention (Chen and Liaw, 2017). However, these sensors also have limitations. They cover only small areas, which means they may not provide a comprehensive overview of the rainforest's condition (Arevalo et al., 2020; Mutiara, Suryana, et al., 2020).

Figure 3 illustrates, using a color scheme, the geographical distribution of the initiatives detailed in Tables 1 to 4. America is depicted in yellow, Europe in green, Asia in blue, and Africa in orange. It highlights a distinct trend in the application of specific technologies across different continents. For example, in Asia, solutions utilizing mission-oriented sensors have been adopted, whereas in the Americas, satellite monitoring and acoustic sensors are employed more commonly.

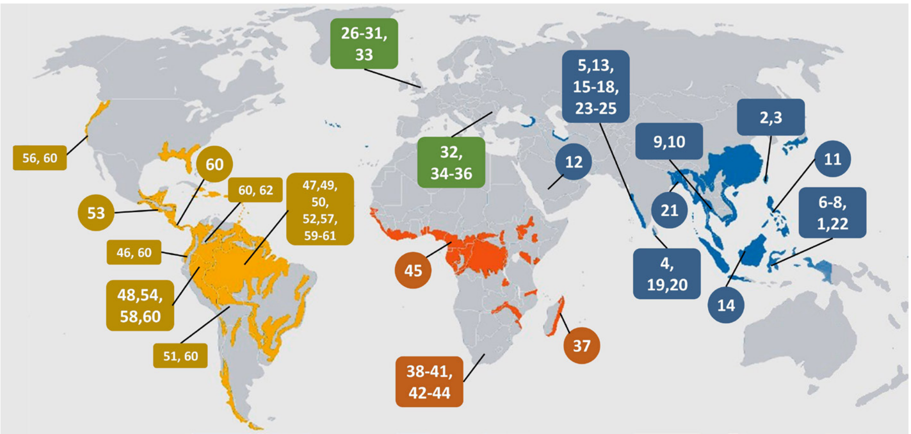

Figure 3. Initiatives for remote monitoring around the world

Requirements for Amazon Remote Monitoring Systems (RMS)

The Amazon Rainforest is famous for its vast wilderness, making the development of a remote monitoring system (RMS) a significant challenge (Oliveira and Figueira, 2021). The harsh environmental conditions, along with limited communication and infrastructure, further complicate the situation. To ensure the effectiveness of an RMS in this unique ecosystem, it must fulfill several requirements. These requirements include the ability to withstand severe weather conditions, provide timely and accurate data to relevant entities, demonstrate cost-effectiveness, and allow for ease of maintenance. The requirements that an RMS should meet are listed below (Kamminga et al., 2018):

A. Stealthiness: Park rangers often feel uneasy about intrusive technologies that significantly alter the environment in ways perceived as unnatural. For instance, solar energy harvesting systems requiring bulky support structures modify the surrounding vegetation's anatomy and are visible to external human agents. Such systems are more prone to detection and interception. For these reasons, the RMS must avoid attracting visual attention by blending in with the environment. The Guardian system (Rainforest Connection, 2023) excels in this regard, thanks to its small size, which allows it to be placed on treetops.

B. Robustness: The RMS must be capable of withstanding various factors, both technical and environmental. A failure in the RMS can occur during a threat, its detection, and the subsequent notification. Therefore, the destruction or failure of any individual component should not result in a total collapse of the RMS, ensuring that the information collected remains intact. The key challenges in the tropical rainforest include flooding in areas near rivers, wildfires during dry seasons caused by falling and burning trees, the presence of insects such as midges attracted to the heat generated by electronic devices, birds that build their nests in the RMS structures, rodents that may damage the cables arranged for the equipment, and other factors. One example of a robust system that has been successfully implemented is Instant Detect 2.0, which helps monitor wildlife in real-time (Zoological Society of London, 2013).

C. Autonomy: The RMS should operate autonomously for periods ranging from a few days to several months, due to the need for stealth during operations and the inaccessibility of the target area. Manual energy replenishment for various RMS modules may not be practical, making autonomous energy systems, such as solar panels and energy-efficient designs, essential. These systems are vital to ensure the continuous operation of the RMS modules throughout the monitoring task. One successful initiative that meets this requirement is the Guardian System (Rainforest Connection, 2023).

D. Coverage: The tropical rainforest, such as the Amazon, is marked by minimal human intervention, leading to limited communication capabilities and infrastructure availability. Consequently, satellite systems and radio communication methods are essential. These two telecommunication approaches address the challenges of traversing the jungle, either by utilizing satellites or by reflecting electromagnetic signals in the ionosphere. In this regard, satellite systems are particularly notable; alternatives that integrate radar and optical imagery (Doblas et al., 2022; Reiche et al., 2018) exemplify this type of system.

E. Scalability: The areas of interest in the tropical rainforest are typically quite large, so the RMS must be scalable. The RMS should accommodate new devices within the system. This scalability can be achieved through either hardware or software.

Hardware modifications should be implementable without significant alterations to the physical system. Scalability also implies that the RMS can be extended to cover larger areas without compromising the requirements outlined in this section. One system that meets this requirement is the Connected Conservation System implemented in Africa (Cisco Systems, 2019).

Final considerations

The Amazon rainforest is one of the most vital ecosystems on the planet, not only because of its biodiversity but also for its role as a global carbon sink and regulator of climate patterns. Its preservation directly aligns with key United Nations Sustainable Development Goals, including climate action, conservation of marine life, protection of wildlife and biodiversity, and the promotion of environmental justice. However, ongoing threats such as deforestation, illegal logging, wildlife trafficking, and resource exploitation pose significant challenges to its sustainability. To tackle these issues, Remote Monitoring Systems (RMS) present a promising solution; however, their effective implementation necessitates addressing both technological feasibility and economic viability.

Based on the analysis presented in this article, a hybrid approach that combines satellite-based monitoring with localized, mission-oriented sensor systems could be an effective strategy, leveraging the strengths of both technologies while addressing their limitations. On one hand, satellite monitoring systems can serve as a backbone, as they are cost-effective on a per-area basis and capable of providing extensive coverage to detect large-scale changes, such as deforestation fronts. Advances in open-access platforms, provided by international agencies, lower entry barriers for their use in the Amazon. However, satellite imagery alone struggles to capture under-canopy activities, such as poaching or illegal logging, highlighting the need for complementary systems.

On the other hand, mission-oriented sensor networks can be proposed for local insights. Deploying networks of acoustic sensors and camera traps in high-risk zones is technically feasible, as these technologies have demonstrated robustness under extreme environmental conditions. Recent advancements in solar-powered and low-energy devices enhance their autonomy, thereby reducing maintenance costs. However, high initial investment costs and infrastructure requirements for data transmission (internet or mobile connectivity) continue to pose significant barriers.

From the perspective of economic and technological integration, it is crucial to prioritize areas with the highest ecological value or threat levels. The incorporation of artificial intelligence (AI) for automated data analysis can further enhance resource utilization by detecting illegal activities or environmental changes in real-time. Collaborations with private companies, non-governmental organizations, and international entities can offer financial and technical support.

This article makes three significant academic contributions to conservation technology: it provides a global perspective by categorizing conservation technologies across continents, offering insights into regional patterns; it addresses the logistical challenges of the Amazon, pinpointing issues in current monitoring strategies; and it introduces parameters for Remote Monitoring Systems (RMS) design, emphasizing essential requirements such as stealthiness, robustness, and scalability, which can also be adapted to other biodiverse ecosystems facing similar threats.

Conclusion

The successful implementation of RMS in the Amazon requires a balance between technological capabilities and economic realities. A hybrid monitoring system that combines satellite imagery with localized sensors presents a feasible and scalable solution. These systems, bolstered by AI and international collaboration, have the potential to revolutionize biodiversity conservation in the Amazon. This article lays the groundwork for crucial strategies to safeguard one of the planet's most vital ecosystems.

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