

Integrated Remote Sensing-Based Framework for Monitoring Volcanic Eruptions and their Impact on Endemic Species in Protected Forest Reserves

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Abstract

Volcanic eruptions present a dual threat to ecological stability and biodiversity, especially in protected forest reserves housing vulnerable endemic species. Conventional monitoring methods often focus on geological parameters while neglecting the cascading ecological effects of eruptions on flora and fauna. This review proposes an integrated remote sensing-based framework that combines satellite imagery, unmanned aerial vehicle (UAV) data, and geographic information systems (GIS) to monitor volcanic activity and assess its spatiotemporal impact on endemic species within conservation zones. The framework employs multi-sensor data fusion, thermal and spectral indices (e.g., NDVI, NBR), and ecological niche modeling to detect habitat degradation, species displacement, and vegetation loss following eruptions. A synthesis of literature highlights the underutilization of advanced geospatial analytics in ecological risk assessment, revealing a critical gap in conservation resilience strategies. By aligning real-time volcanic monitoring with biodiversity conservation, this study emphasizes the need for integrated early-warning systems that not only forecast geophysical hazards but also proactively safeguard ecological integrity. The proposed approach supports data-driven decision-making for conservation managers, emergency responders, and environmental policymakers, ensuring a holistic response to volcanic disturbances in biodiversity hotspots.

Keywords: Remote Sensing, Volcanic Eruptions, Endemic Species, Protected Forest Reserves, Monitoring Framework.

I. INTRODUCTION

➤ Background of the Study

Volcanic eruptions are significant geological events that can profoundly affect the ecosystems of protected forest reserves, especially concerning endemic species. These natural disasters can lead to habitat destruction, altered resource availability, and increased vulnerability to invasive species, collectively threatening the survival of native flora and fauna. Understanding these impacts is crucial for developing effective conservation strategies. Recent studies have highlighted the complex interactions between volcanic activity and forest ecosystems. For instance, research on the Canary pine forest demonstrated that volcanic eruptions, combined with previous wildfires,

significantly influence seedling establishment in the first year post-disturbance. This finding underscores the compounded effects of multiple disturbances on forest regeneration (Pérez-Cruzado et al., 2024). Similarly, the eruption of Mauna Loa in Hawaii in late 2022 posed significant threats to native habitats. The Pu'u Maka'ala Natural Area Reserve, rich in endangered species, was at risk as lava flows approached. Fortunately, the lava diverted, sparing the reserve. However, the event highlighted the vulnerability of such reserves to volcanic activity and the necessity for vigilant monitoring and preparedness (Hawaii Department of Land and Natural Resources, 2022). In the Comoros Islands, volcanic activity has exacerbated threats to native forests and species. The interaction between volcanic eruptions and

human activities, such as agriculture, has led to significant habitat loss. This loss endangers species like the fruit bat, emphasizing the need for integrated conservation approaches that address both natural and anthropogenic threats (Baker et al., 2023). Furthermore, historical volcanic events have long-term implications for endemic species. A study on the Mascarene petrel in Réunion Island revealed that past volcanic activity has predisposed this seabird to negative anthropogenic impacts, affecting its current conservation status. This finding suggests that historical natural events should be considered when assessing species' vulnerabilities to modern threats (Teixeira et al., 2024). These instances highlight the intricate relationship between volcanic activity and forest ecosystems, particularly concerning endemic species in protected reserves. They emphasize the necessity for comprehensive research and monitoring to inform conservation strategies that mitigate the adverse effects of volcanic disturbances.

➤ *Problem Statement*

Despite the critical importance of protected forest reserves in preserving biodiversity, these areas remain vulnerable to the impacts of volcanic eruptions, which can lead to significant ecological disturbances. Traditional monitoring approaches often focus on geological parameters, neglecting the cascading effects on ecosystems and endemic species. This oversight hampers effective conservation efforts and the development of resilient management strategies. The integration of remote sensing technologies offers a promising avenue to bridge this gap, enabling comprehensive monitoring of both volcanic activity and its ecological repercussions. Recent studies underscore the limitations of conventional monitoring methods. For instance, Pérez-Cruzado et al. (2024) highlight that while traditional approaches provide valuable geological data, they often fail to capture the nuanced impacts of volcanic events on forest regeneration and species distribution. Similarly, the Hawaii Department of Land and Natural Resources (2022) reported that while geological monitoring during the Mauna Loa eruption was robust, ecological assessments lagged, delaying timely conservation responses. These instances illustrate the need for an integrated monitoring framework that encompasses both geological and ecological dimensions. The vulnerability of endemic species to volcanic disturbances further complicates conservation efforts. Teixeira et al. (2024) demonstrate that historical volcanic activity has predisposed certain species, like the Mascarene petrel, to heightened sensitivity to modern anthropogenic threats. This underscores the importance of considering both historical and contemporary factors in conservation planning. Furthermore, the dynamic nature of volcanic hazards necessitates real-time monitoring capabilities. Advancements in remote sensing technologies, such as thermal infrared sensors and multispectral imaging, enable the continuous observation of volcanic activity and its immediate effects on surrounding ecosystems (James et al., 2023). These technologies facilitate the rapid assessment of habitat changes, species displacement, and other ecological impacts, thereby informing timely conservation interventions. The existing gap in integrated

monitoring systems that concurrently assess volcanic activity and its ecological impacts presents a significant challenge to effective conservation in protected forest reserves. Addressing this gap through the adoption of advanced remote sensing technologies is imperative to enhance our capacity to safeguard biodiversity in the face of volcanic disturbances.

➤ *Aim and Objectives of the Study*

This study aims to develop an integrated remote sensing-based framework for monitoring volcanic eruptions and assessing their impact on endemic species within protected forest reserves. The framework seeks to enhance the understanding of how volcanic disturbances affect biodiversity and to inform conservation strategies that mitigate these impacts.

➤ *Scope and Delimitation*

This study focuses on developing an integrated remote sensing-based framework to monitor volcanic eruptions and assess their impact on endemic species within protected forest reserves. The geographical scope of this research is limited to forest reserves that are situated within regions prone to volcanic activity, specifically those with a significant presence of endemic species whose survival is highly vulnerable to environmental changes. The study will primarily focus on volcanic events that have occurred in the past five years, with an emphasis on active volcanoes where the potential for future eruptions remains high. The ecological scope of the study is confined to the impact of volcanic eruptions on vegetation loss, habitat degradation, and the displacement of endemic species. The research will exclude the effects of volcanic eruptions on broader regional ecosystems that do not directly affect protected forest reserves. Additionally, the study will not consider the socioeconomic or human impacts of volcanic activity, as the focus remains strictly on ecological and biodiversity-related concerns. Data acquisition will be based on remote sensing technologies such as satellite imagery, UAVs, and other geospatial tools that provide high-resolution monitoring capabilities. While the study will incorporate field validation for the ecological data, the scope does not extend to extensive ground-based monitoring of all species within the selected reserves. Furthermore, the study will be delimited to analyzing the direct and immediate impacts of volcanic activity on biodiversity, rather than long-term ecological recovery processes. By focusing on these specific parameters, this study aims to provide actionable insights into how remote sensing technologies can be leveraged to enhance conservation efforts in areas vulnerable to volcanic disturbances.

➤ *Significance of the Study*

The significance of this study lies in its potential to advance both the scientific understanding and practical management of protected forest reserves in regions vulnerable to volcanic activity. Volcanic eruptions, although natural events, pose severe threats to the biodiversity of ecosystems, especially in forest reserves that house endemic species. These ecosystems, which often serve as refuges for species at risk of extinction, face

immediate destruction from lava flows, ash deposition, and long-term habitat alteration. By developing an integrated remote sensing-based framework, this study seeks to provide a comprehensive tool for monitoring volcanic activity and assessing its direct ecological consequences on biodiversity. This research will contribute to the field of environmental monitoring by advancing the integration of remote sensing technologies with ecological assessments, enabling a more effective understanding of volcanic disturbances and their aftermath. The framework will help bridge gaps in current monitoring systems, which typically prioritize geological data over ecological impacts, thus improving the effectiveness of conservation strategies. Additionally, it offers a real-time, scalable solution for managers and policymakers to make informed decisions regarding habitat restoration and species protection in volcanic regions. Furthermore, the study will offer valuable insights into the long-term resilience of endemic species, providing data that could guide conservation actions aimed at minimizing habitat loss and species displacement. The adoption of this framework will not only support biodiversity conservation in areas affected by volcanic activity but also strengthen the broader resilience of protected areas to other natural disasters, contributing to sustainable ecosystem management in the face of climate change and increasing natural hazards. Ultimately, this research holds the potential to influence national and

global conservation policies, making it a significant contribution to the protection of some of the most ecologically sensitive and critical landscapes on Earth.

II. LITERATURE REVIEW

➤ *Remote Sensing Technologies for Volcanic Monitoring*

Remote sensing technologies have become indispensable tools in the monitoring of volcanic activity, offering comprehensive, real-time data that are crucial for understanding and mitigating volcanic hazards. These technologies encompass a range of sensors and platforms, including satellite-based instruments, unmanned aerial vehicles (UAVs), and ground-based systems, each contributing unique capabilities to volcanic surveillance. Satellite-based remote sensing provides extensive spatial coverage and frequent revisit times, enabling the continuous observation of volcanic features. In particular, thermal infrared (TIR) sensors aboard satellites are adept at detecting thermal anomalies associated with volcanic activity. These sensors measure the radiative power emitted by volcanic surfaces, facilitating the assessment of eruption intensity and the identification of active volcanic centers (Chatterjee et al., 2025). Additionally, synthetic aperture radar (SAR) systems, such as those employed in the VISTA project, offer high-resolution imagery that can detect ground deformation indicative of volcanic unrest, even in cloud-covered regions (ESA, 2025).

Table 1 Integrative Remote Sensing Approaches for Volcanic Activity Monitoring and Hazard Mitigation

Technology Type	Platform	Sensor/Instrument	Application	Example/Reference
Satellite-Based	Orbital Satellites	Thermal Infrared (TIR), SAR	Detect thermal anomalies, monitor surface temp & ground uplift	Chatterjee et al., 2025; ESA, 2025
UAV-Based	Unmanned Aerial Vehicles (UAVs)	Multispectral & Thermal Cameras	High-res monitoring of gas plumes, ash clouds, and surface flux	D'Arcy et al., 2022
Ground-Based	Static Terrestrial Stations	TIR Cameras, Multi-Gas Analyzers	Measure gas compositions, fluxes, and surface thermal properties	Aiuppa et al., 2023
Integrated Systems	Multi-platform Fusion	Cross-sensor Data Integration	Enhance early warning, hazard mapping, eruption prediction	Synthesis from multi-source observations
Specialized Projects/Systems	Institutional & Research-led	Project-based Sensors (e.g., VISTA)	Track deformation in cloud-covered regions, validate models	ESA VISTA Project (ESA, 2025)

Table 1 Plays a vital role in monitoring volcanic activity by providing real-time data from satellites, drones, and ground-based instruments. Satellites detect heat and ground changes over large areas, while drones capture detailed images and gas emissions from hard-to-reach spots. Ground instruments offer precise measurements of gases and surface temperatures. When combined, these tools give scientists a clearer and more complete picture of volcanic behavior, helping to predict eruptions and manage risks effectively. UAVs equipped with multispectral and thermal cameras provide high-resolution, localized data that are invaluable for detailed assessments of volcanic landscapes. These platforms can access areas that are otherwise hazardous or inaccessible, allowing for the collection of data on gas emissions, ash plumes, and surface changes with minimal risk to

personnel (D'Arcy et al., 2022). For instance, drones have been utilized to measure CO₂ emissions at volcanoes like Poás in Costa Rica, offering insights into volcanic degassing processes (D'Arcy et al., 2022). Ground-based remote sensing technologies, such as thermal infrared cameras and multi-component gas analyzers, play a critical role in providing detailed, high-precision measurements of volcanic emissions. These instruments are capable of detecting specific gas species, estimating fluxes, and characterizing the thermal properties of volcanic surfaces, thereby enhancing the understanding of volcanic processes (Aiuppa et al., 2023). The integration of these remote sensing technologies facilitates a comprehensive approach to volcanic monitoring, enabling the detection of early warning signs, assessment of eruption potential, and evaluation of environmental

impacts. By combining data from various platforms, researchers and authorities can obtain a more accurate and holistic view of volcanic activity, which is essential for effective hazard assessment and risk management strategies.

➤ *Biodiversity and Ecological Sensitivity of Forest Reserves*

Protected forest reserves are critical sanctuaries for biodiversity, often harboring a high concentration of endemic species that are uniquely adapted to their specific environments. These ecosystems are particularly sensitive to disturbances, such as volcanic eruptions, which can

have profound and lasting impacts on their structure and function. The intricate relationships between species and their habitats mean that even minor alterations can lead to significant ecological consequences. For instance, the Pu'u Maka'ala Natural Area Reserve in Hawaii, located within the Mauna Loa Forest Reserve, is home to numerous endangered species. During the 2022 Mauna Loa eruption, the reserve was at risk as lava flows approached. Fortunately, the lava diverted, sparing the reserve; however, the event underscored the vulnerability of such areas to volcanic activity and the necessity for vigilant monitoring and preparedness. Similarly, the Canary pine forests in the Canary Islands have experienced compounded threats from both volcanic eruptions and wildfires.



Fig 1 Volcanoes and Vital Habitats: The Fragile Balance of Biodiversity in Forest Reserves

Figure 1 Captures the profound beauty and vulnerability of protected forest reserves, showcasing their rich biodiversity alongside looming volcanic threats. From Hawaii's Pu'u Maka'ala to the Canary Islands and New Zealand's Egmont National Park, these ecosystems are sanctuaries for endemic species uniquely adapted to dynamic volcanic landscapes. The visual narrative underscores how disturbances—like eruptions and wildfires—can ripple through these habitats, impacting regeneration and survival. Despite the dramatic forces of nature, the resilience and ecological significance of these forests call for continued vigilance, conservation, and preparedness to safeguard the intricate web of life they support. A study investigating the aftermath of the 2021 Cumbre Vieja eruption found that these combined disturbances significantly affected first-year seedling establishment, highlighting the compounded effects of multiple disturbances on forest regeneration. In New Zealand, Egmont National Park encompasses diverse vegetation developed in an environment of frequent volcanic activity. The park provides the only habitat for many bird species in the Egmont Ecological District,

emphasizing the importance of such reserves in supporting unique biodiversity. Furthermore, the Trans-Mexican Volcanic Belt, a region characterized by volcanic activity, is home to a variety of endemic species. A multi-taxa analysis in this area identified priority conservation zones, underscoring the need for targeted conservation efforts in regions affected by volcanic activity. These examples illustrate the delicate balance within protected forest reserves and the significant threats posed by volcanic activity. The loss or alteration of these habitats can lead to declines in endemic species populations and disrupt ecological processes, making it imperative to understand and mitigate the impacts of volcanic disturbances on these sensitive ecosystems.

➤ *Impact of Volcanic Eruptions on Flora and Fauna*

Volcanic eruptions can have profound and multifaceted impacts on forest ecosystems, particularly in regions housing endemic species. These impacts range from immediate habitat destruction to long-term ecological shifts that can threaten biodiversity (Ijiga, et al., 2024). The severity and nature of these effects depend on

factors such as eruption magnitude, proximity to sensitive habitats, and the resilience of local species. One immediate consequence of volcanic activity is the destruction of habitats (Cyuma, et al., 2025). For example, the 2021 eruption of Cumbre Vieja in the Canary Islands led to the burial of extensive pine forests under lava flows, resulting

in the loss of critical habitats for numerous species. Similarly, the 2024 eruption of Kīlauea in Hawaii, while primarily confined to the summit caldera, still posed risks to nearby ecosystems through the emission of volcanic gases and ash, which can degrade air and soil quality, affecting plant and animal health.

Table 2 Ecological Consequences of Volcanic Eruptions on Flora, Fauna, and Endemic Species

Impact Type	Example Location/Event	Ecological Consequence	Species Affected	Long-Term Implication
Immediate Habitat Loss	Cumbre Vieja, Canary Islands (2021)	Lava flows buried forests	Pine-dependent species	Permanent loss of habitat and decline in biodiversity
Air and Soil Contamination	Kīlauea, Hawaii (2024)	Volcanic gases and ash degrade environmental quality	Local flora and fauna near summit caldera	Deterioration of health and reproductive viability
Soil and Water Disruption	Post-eruption, Canary Islands (2021)	Altered soil and water chemistry affected plant regeneration	Seedlings and dependent herbivores	Impaired forest recovery and disruption of food chains
Endemic Species Vulnerability	Mascarene Islands – historical activity	Increased susceptibility to other threats due to habitat loss	Mascarene petrel and other narrow-range endemics	Compounded conservation challenges and risk of extinction
Conservation and Monitoring	Global Volcanic Zones	Need for integrated geological-ecological response systems	Broad range of sensitive species	Informed planning and early interventions for biodiversity protection

Table 2 Significantly disrupt forest ecosystems, causing both immediate and long-term ecological damage. Events like the 2021 Cumbre Vieja eruption led to widespread habitat loss as lava flows buried pine forests, while eruptions such as Kīlauea in 2024 released toxic gases and ash that degraded soil and air quality. These impacts hinder plant regeneration, disrupt food chains, and threaten species survival—particularly endemic organisms with narrow habitat ranges, like the Mascarene petrel. The altered soil composition, water chemistry, and compounding effects from prior disturbances (e.g., wildfires) further impede ecological recovery. Therefore, integrated conservation strategies that align geological monitoring with biodiversity assessments are essential for safeguarding vulnerable species and promoting ecosystem resilience in volcanic regions. Beyond immediate destruction, volcanic eruptions can alter the landscape in ways that disrupt ecological processes. The deposition of ash and pyroclastic materials can change soil composition and water chemistry, affecting plant growth and the species that depend on these plants. For instance, in the aftermath of the 2021 eruption in the Canary Islands, researchers observed a decline in seedling establishment due to the combined effects of volcanic ash and previous wildfire damage, highlighting the compounded threats to forest regeneration. Furthermore, volcanic activity can exacerbate the vulnerability of endemic species. Species that are already at risk due to their limited distribution or specialized habitat requirements may find it challenging to recover from volcanic disturbances. A study on the Mascarene petrel, an endemic seabird, revealed that past volcanic activity had predisposed the species to negative anthropogenic impacts, affecting its current conservation.

The cumulative effects of volcanic eruptions underscore the need for integrated monitoring and conservation strategies. By combining geological observations with ecological assessments, conservationists can better understand the full scope of volcanic impacts and develop more effective measures to protect vulnerable species and habitats.

➤ *Integrated Remote Sensing and GIS for Habitat Impact Assessment*

The integration of remote sensing and Geographic Information Systems (GIS) has become indispensable in assessing and managing the impacts of volcanic eruptions on forest habitats. These technologies enable comprehensive monitoring of environmental changes, facilitating informed decision-making for conservation and restoration efforts. Remote sensing provides valuable data through various platforms, including satellites and unmanned aerial vehicles (UAVs) (Ijiga, et al., 2024). For instance, the European Space Agency's Sentinel-2 satellites offer high-resolution multispectral imagery, which is instrumental in monitoring vegetation health and land cover changes post-eruption. Similarly, UAVs equipped with multispectral sensors allow for detailed, localized assessments of affected areas, capturing data on vegetation stress and recovery over time. GIS serves as a powerful tool for analyzing and visualizing spatial data, enabling the assessment of habitat suitability and the identification of areas requiring restoration. By integrating remote sensing data with GIS, researchers can create habitat suitability models that predict the potential for species re-establishment in disturbed areas.

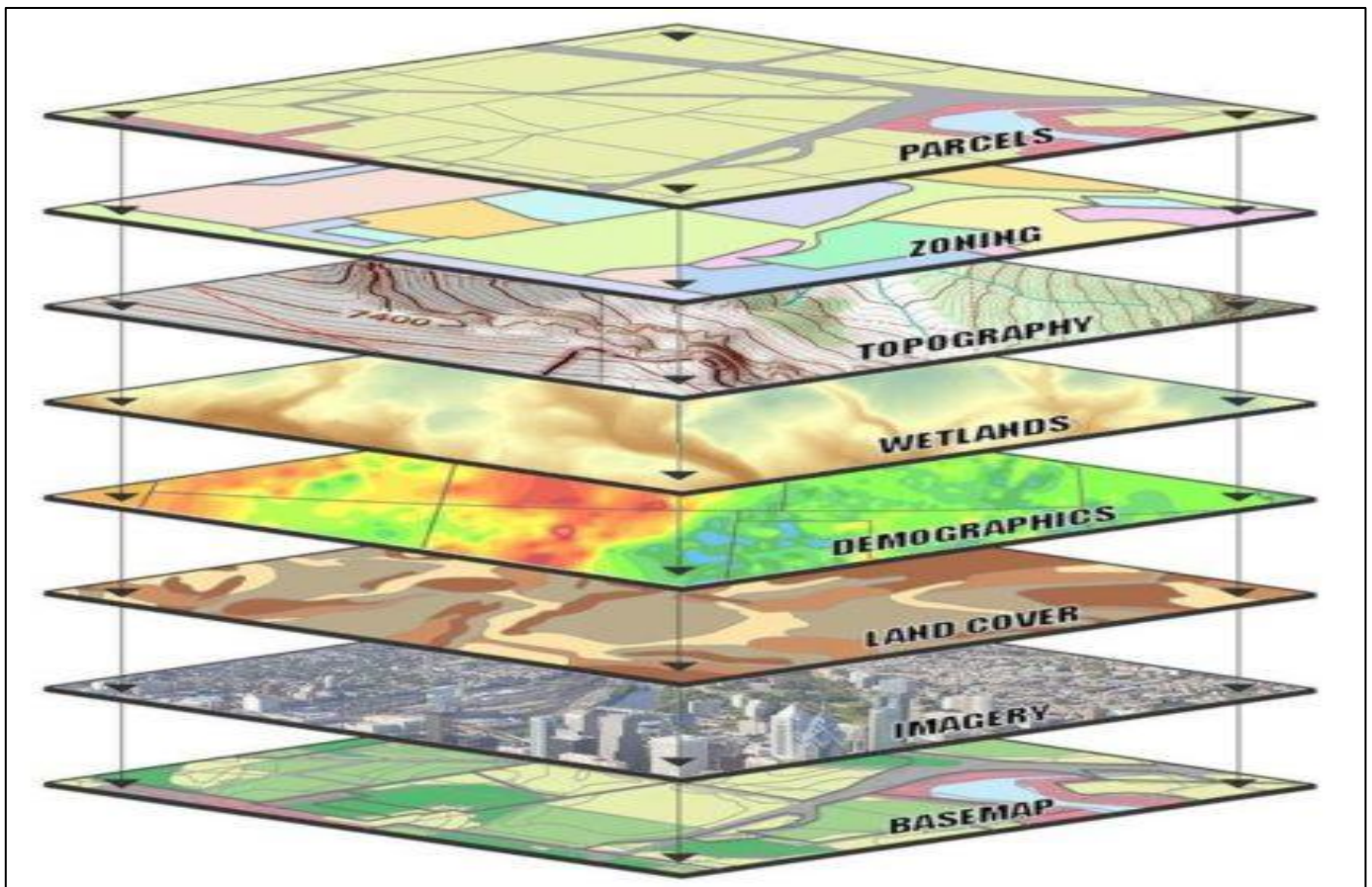


Fig 2 Layered Spatial Data Representation in Geographic Information Systems (GIS) (Plansup.2025)

Figure 2 Captures the essence of the visualized data layers such as parcels, zoning, topography, wetlands, demographics, land cover, imagery, and basemaps—all key components in a GIS used for spatial analysis and decision-making. This approach has been successfully applied in various studies, such as the assessment of habitat suitability for the Mountain Nyala in Bale Mountains National Park, demonstrating the efficacy of GIS in habitat analysis. The combination of remote sensing and GIS also facilitates the monitoring of ecological recovery processes. For example, a study monitoring vegetation recovery after forest and land fires in the Bromo Volcano area utilized Sentinel-2 imagery and GIS analysis to evaluate changes in vegetation cover and assess the effectiveness of restoration efforts. Such integrated approaches provide valuable insights into the dynamics of habitat recovery and the factors influencing it. Furthermore, the application of these technologies extends to the evaluation of forest resilience. A systematic literature review highlighted the use of remote sensing and GIS in assessing forest resilience, emphasizing their role in quantifying attributes and indicators that contribute to forest stability and recovery. These tools enable the identification of vulnerable areas and the implementation of targeted conservation strategies. The integration of remote sensing and GIS is crucial for effective habitat impact assessment following volcanic eruptions. These technologies provide comprehensive, spatially explicit data that inform conservation planning and facilitate the restoration of affected ecosystems, ensuring the persistence of biodiversity in forest reserves.

➤ *Gaps in Literature and Opportunities for Innovation*

While significant progress has been made in utilizing remote sensing and Geographic Information Systems (GIS) for assessing habitat impacts following volcanic eruptions, several gaps persist in the literature that present opportunities for innovation. These gaps include limitations in spatial and temporal resolution, challenges in integrating diverse data sources, insufficient ecological modeling, underutilization of advanced machine learning techniques, and the need for region-specific studies. Current remote sensing technologies, such as Synthetic Aperture Radar (SAR) and optical imagery, often lack the spatial and temporal resolution required to capture rapid changes in volcanic landscapes. A study by Ganci et al. (2023) suggests that a pixel size of 13 meters and a temporal resolution of one day or less are necessary to effectively monitor topographic changes during volcanic events. This indicates a need for higher-resolution data to accurately assess habitat alterations in near real-time. Additionally, integrating SAR and optical data through deep learning-based fusion methods has shown promise in improving land use and land cover classification; however, challenges remain in addressing the intrinsic differences between these data types (Irfan et al., 2025). Ecological modeling efforts often fall short in simulating the complex interactions between volcanic disturbances and habitat recovery processes. Risna et al. (2023) conducted a systematic literature review and found that while remote sensing and GIS are widely used in forest resilience research, there is a lack of comprehensive models that incorporate ecological dynamics post-eruption. This gap highlights the need for models that integrate ecological

variables to predict and manage habitat recovery effectively (Idoko, et al., 2024). The application of machine learning techniques in analyzing remote sensing data for habitat impact assessment remains underexplored. Recent advancements in machine learning offer the potential to enhance the accuracy and efficiency of habitat suitability analyses. For instance, a study by Liu et al. (2024) demonstrated the use of a dual-branch embedded multivariate attention network for hyperspectral remote sensing classification, which could be adapted to assess habitat changes following volcanic events. Furthermore, there is a scarcity of region-specific studies that address the unique ecological contexts of different volcanic areas. Research by Zhang et al. (2024) on the Guallatiri volcano in Chile emphasizes the importance of localized GIS-based hazard and risk assessments, suggesting that similar approaches should be applied to other regions to account for local ecological and geological conditions (Idoko, et al., 2024). Addressing these gaps presents significant opportunities for innovation in the field of habitat impact assessment following volcanic eruptions. Advancements in high-resolution remote sensing technologies, improved integration of diverse data sources, development of comprehensive ecological models, application of machine learning techniques, and region-specific studies are essential to enhance the effectiveness of conservation and restoration efforts in volcanic landscapes.

III. METHODOLOGY

➤ *Conceptual Framework of the Remote Sensing-Based Monitoring System*

The conceptual framework for a remote sensing-based monitoring system integrates various technological components to assess and manage the impacts of volcanic eruptions on forest habitats. This framework encompasses data acquisition, processing, analysis, and dissemination stages, facilitating comprehensive environmental monitoring. At the core of this system are remote sensing technologies, including satellites, unmanned aerial vehicles (UAVs), and ground-based sensors. Satellites such as the European Space Agency's Sentinel-2 provide high-resolution multispectral imagery, enabling the monitoring of vegetation health and land cover changes over time. UAVs equipped with multispectral and thermal sensors offer detailed, localized data, allowing for the assessment of specific areas affected by volcanic activity. Ground-based sensors, including thermal infrared cameras and gas analyzers, complement these technologies by providing real-time data on surface temperature and gas emissions, which are critical for understanding the immediate impacts of volcanic events. The integration of these data sources is facilitated through Geographic Information Systems (GIS), which enable the spatial analysis and visualization of environmental changes. GIS platforms support the creation of habitat suitability models, allowing for the assessment of potential impacts on endemic species and the identification of areas requiring restoration.

Table 3 A Multilayered Remote Sensing Framework for Biodiversity Monitoring and Forest Habitat Assessment in Volcanic Regions

Component	Technology/Tool	Function	Output/Product	Application
Data Acquisition	Satellites (e.g., Sentinel-2), UAVs, Sensors	Collect imagery, thermal data, and gas emission readings	Multispectral images, thermal maps, gas concentration data	Monitoring vegetation health, surface temperature, emissions
Data Integration	Geographic Information Systems (GIS)	Compile and align spatial datasets	Georeferenced environmental layers	Habitat analysis and land cover change detection
Data Analysis	Machine Learning Algorithms	Classify land cover, detect change, model ecosystem dynamics	Habitat quality maps, predictive models	Risk assessment and restoration planning
Biodiversity Monitoring	Essential Biodiversity Variables (EBVs)	Track species distribution and population metrics	Biodiversity indicators and trends	Measure conservation effectiveness and ecosystem health
Decision Support	Integrated Monitoring System	Combine all outputs for strategic planning	Actionable insights for conservation and restoration	Informed policymaking and emergency response

Table 3 Provides a comprehensive, technology-driven approach to assess the ecological impacts of volcanic eruptions on forest habitats. It integrates satellite imagery, UAV data, and ground-based sensor readings to capture thermal anomalies, vegetation health, and gas emissions. These data are spatially processed using Geographic Information Systems (GIS), enabling habitat mapping and land cover change detection. Advanced machine learning algorithms further enhance the analysis by classifying land types and identifying degradation patterns. By incorporating Essential Biodiversity Variables

(EBVs), the system allows for standardized tracking of species distributions and ecosystem health over time. Together, these components create a dynamic decision-support system that informs conservation strategies, supports ecological restoration, and strengthens biodiversity resilience in volcanic landscapes. Additionally, the integration of machine learning algorithms enhances the analysis by enabling the classification of land cover types and the detection of changes in habitat quality. Furthermore, the incorporation of Essential Biodiversity Variables (EBVs) into this

framework provides standardized metrics for monitoring biodiversity changes. EBVs, such as species distribution and population abundance, offer quantifiable indicators that can be tracked over time, facilitating the assessment of ecosystem health and the effectiveness of conservation efforts. The conceptual framework of a remote sensing-based monitoring system combines advanced technologies and standardized metrics to provide a comprehensive approach to monitoring and managing the impacts of volcanic eruptions on forest habitats. This integrated system supports informed decision-making and contributes to the conservation of biodiversity in affected areas.

➤ *Data Acquisition and Preprocessing*

The success of a remote sensing-based monitoring system for assessing the impact of volcanic eruptions on forest habitats is heavily reliant on the effective acquisition and preprocessing of data. This initial phase forms the

foundation for accurate analysis and interpretation. The acquisition process involves the systematic collection of remote sensing data from various sources, including satellites, unmanned aerial vehicles (UAVs), and ground-based sensors. Satellites such as the European Space Agency's Sentinel-2 offer high-resolution multispectral imagery that facilitates continuous monitoring of vegetation health and land cover changes. UAVs equipped with multispectral and thermal sensors provide high-resolution, localized data that are particularly useful for evaluating areas directly affected by volcanic activity. Ground-based sensors, including thermal infrared cameras and gas analyzers, provide real-time data on temperature fluctuations and gas emissions, which are critical for understanding the immediate effects of volcanic events on ecosystems. Once the data is acquired, preprocessing is essential to enhance its quality and ensure its utility for subsequent analysis.

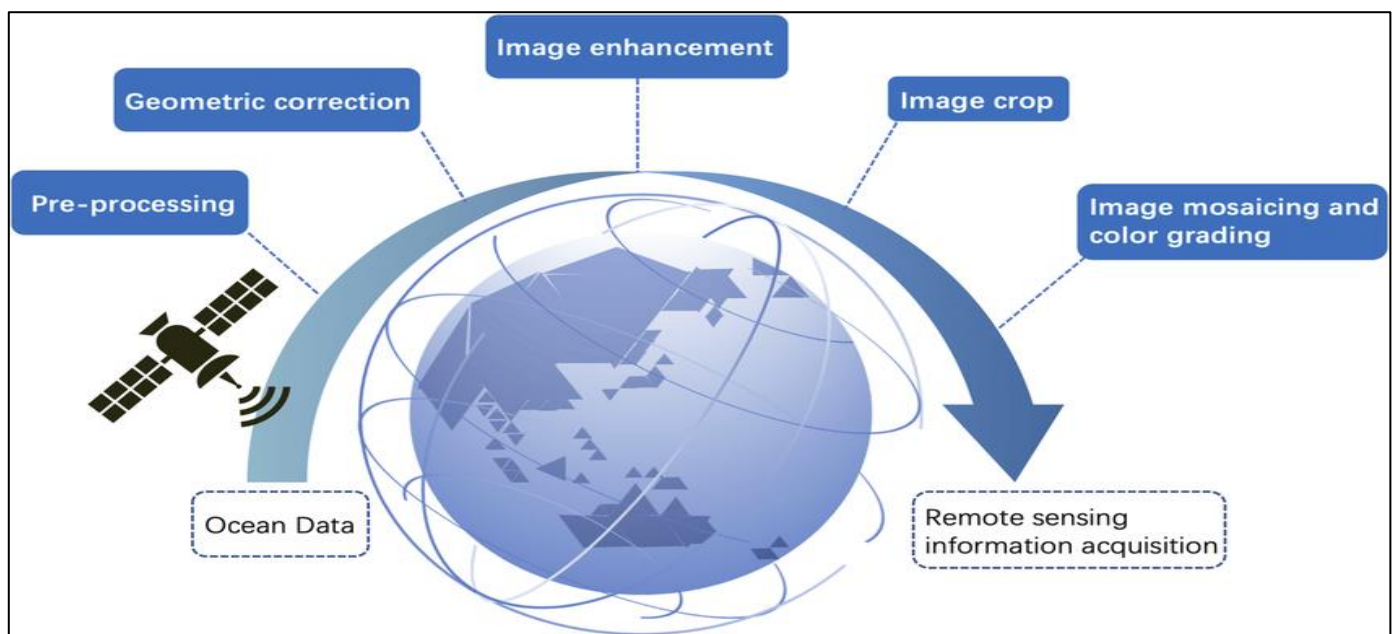


Fig 3 Workflow of Ocean Data Acquisition and Preprocessing in Remote Sensing (Frontiers in Earth Science. 2025)

Figure 3 Illustrates the workflow of remote sensing-based ocean data acquisition and preprocessing, highlighting the key steps involved in transforming raw satellite data into usable geospatial information. Beginning with the reception of ocean data from satellites, the process involves several preprocessing tasks, including geometric correction to align images spatially, and enhancements to improve image clarity. Additional steps such as image cropping, mosaicing, and color grading are applied to refine the visual quality and continuity of data. Collectively, these processes support the effective acquisition of remote sensing information for environmental monitoring, oceanographic analysis, and informed decision-making. Preprocessing involves several key steps, including radiometric calibration to correct for sensor irregularities and atmospheric conditions, geometric correction to align data to a common coordinate system, and cloud and shadow masking to remove affected pixels that could distort surface feature interpretation. Furthermore, noise reduction techniques, such as applying filters to minimize random variations, and image fusion,

which combines data from different sensors to improve spatial and spectral resolution, are crucial for enhancing the quality of the acquired data. Machine learning algorithms also play an essential role in refining data, as deep learning models are increasingly used for classifying land cover types and detecting subtle changes in forest structure post-eruption. Ground truthing, involving the collection of field data to validate and calibrate remote sensing information, ensures the accuracy of the monitoring system. Through these combined acquisition and preprocessing methods, the system establishes a reliable data set for assessing the impact of volcanic eruptions on forest habitats, informing effective conservation and restoration efforts.

➤ *Change Detection and Volcanic Activity Mapping*

Change detection and volcanic activity mapping are pivotal components in assessing the impacts of volcanic eruptions on forest habitats. These processes involve the systematic analysis of temporal remote sensing data to identify and quantify alterations in the landscape resulting

from volcanic events. By leveraging advanced imaging technologies, researchers can monitor surface deformations, lava flow extents, and vegetation changes, thereby providing critical insights into the dynamics of volcanic activity and its ecological consequences. Satellite-based remote sensing platforms, such as the

European Space Agency's Sentinel-1 and Sentinel-2 missions, offer valuable data for volcanic monitoring. Sentinel-1's Synthetic Aperture Radar (SAR) capabilities enable the detection of ground deformations through Interferometric SAR (InSAR) techniques, allowing for the measurement of surface displacement with high precision.

Table 4 Integrated Remote Sensing and Machine Learning Framework for Volcanic Change Detection and Ecological Impact Mapping

Component	Technology/Tool	Functionality	Output/Product	Application
Surface Deformation Monitoring	Sentinel-1 SAR + InSAR Techniques	Detect ground displacement and volcanic inflation	High-resolution deformation maps	Early warning of volcanic unrest and ground instability
Vegetation & Land Cover Change	Sentinel-2 Multispectral Imagery	Assess vegetation stress and land cover variation	NDVI change maps, habitat degradation overlays	Ecological impact analysis and forest recovery planning
Thermal Anomaly Detection	MODIS (Terra/Aqua), VIIRS (Suomi NPP)	Identify active lava flows and surface temperature anomalies	Hotspot maps, thermal anomaly alerts	Real-time eruption detection and lava flow tracking
Data Integration & Visualization	Geographic Information Systems (GIS)	Combine spatial datasets for modeling and hazard mapping	Risk zones, lava path simulations, ash dispersion models	Restoration prioritization, infrastructure and ecosystem risk assessment
Automated Mapping & Classification	Deep Learning (e.g., CNNs)	Analyze satellite imagery to detect and classify volcanic features	Automated change detection layers, classified lava zones	Enhanced mapping accuracy, faster response in dynamic eruption scenarios

Table 4 Highlights how different technologies and tools are integrated to monitor and map volcanic activity and its environmental impacts. It shows that Sentinel-1 with InSAR techniques is used to highlight ground deformation, while Sentinel-2 imagery highlights vegetation and land cover changes. Thermal sensors like MODIS and VIIRS highlight active lava flows and surface heat anomalies. GIS platforms highlight affected zones by integrating spatial data, enabling detailed mapping and simulation of hazards. Finally, machine learning models highlight subtle environmental changes by automating the detection and classification of volcanic features, improving the accuracy and speed of response. Sentinel-2's multispectral imagery facilitates the assessment of vegetation health and land cover changes, which are essential for evaluating the ecological impacts of volcanic eruptions. These datasets, when analyzed over time, provide a comprehensive view of the spatial and temporal changes associated with volcanic activity. In addition to optical and radar satellite imagery, thermal infrared data play a crucial role in detecting volcanic hotspots and assessing thermal anomalies. The Moderate Resolution Imaging Spectroradiometer (MODIS) aboard NASA's Terra and Aqua satellites, along with the Visible Infrared Imaging Radiometer Suite (VIIRS) on the Suomi NPP satellite, offer thermal infrared observations that are instrumental in identifying active lava flows and elevated surface temperatures. These thermal signatures are indicative of ongoing volcanic activity and are essential for real-time monitoring and hazard assessment. Geospatial information systems (GIS) serve as powerful tools for integrating and analyzing multi-source remote sensing data. By overlaying change detection results with

topographic and land use maps, GIS platforms enable the delineation of affected areas, the assessment of eruption impacts on infrastructure and ecosystems, and the identification of regions requiring immediate attention or restoration efforts. Furthermore, GIS-based modeling can predict potential future hazards by simulating lava flow paths and ash dispersion patterns, thereby aiding in disaster preparedness and risk management strategies. Machine learning algorithms, particularly deep learning models, have been increasingly applied to enhance the accuracy and efficiency of volcanic activity mapping. These models can automatically classify and interpret complex remote sensing data, distinguishing between various land cover types and detecting subtle changes that may be indicative of volcanic activity. For instance, convolutional neural networks (CNNs) have been employed to analyze high-resolution satellite imagery, facilitating the identification of lava flows and other volcanic features with high accuracy. The integration of advanced remote sensing technologies, GIS platforms, and machine learning algorithms provides a robust framework for change detection and volcanic activity mapping. This integrated approach enhances our ability to monitor and assess the impacts of volcanic eruptions on forest habitats, thereby informing effective conservation and management strategies.

➤ *Habitat Impact and Species Distribution Modeling*

The assessment of habitat impacts and species distribution following volcanic eruptions is crucial for understanding ecological changes and informing conservation strategies. Species Distribution Models (SDMs) have emerged as essential tools in this context,

enabling the prediction of species' potential distributions based on environmental variables and occurrence data. These models integrate remote sensing data, such as vegetation indices and land cover maps, with species occurrence records to estimate habitat suitability across different temporal and spatial scales. Recent advancements in SDMs have enhanced their application in post-eruption scenarios. For instance, ensemble modeling

approaches, which combine multiple algorithms to improve prediction accuracy, have been employed to assess the impact of volcanic activity on species distributions. These models consider various environmental factors, including temperature, precipitation, and vegetation cover, to predict shifts in species habitats resulting from volcanic disturbances.

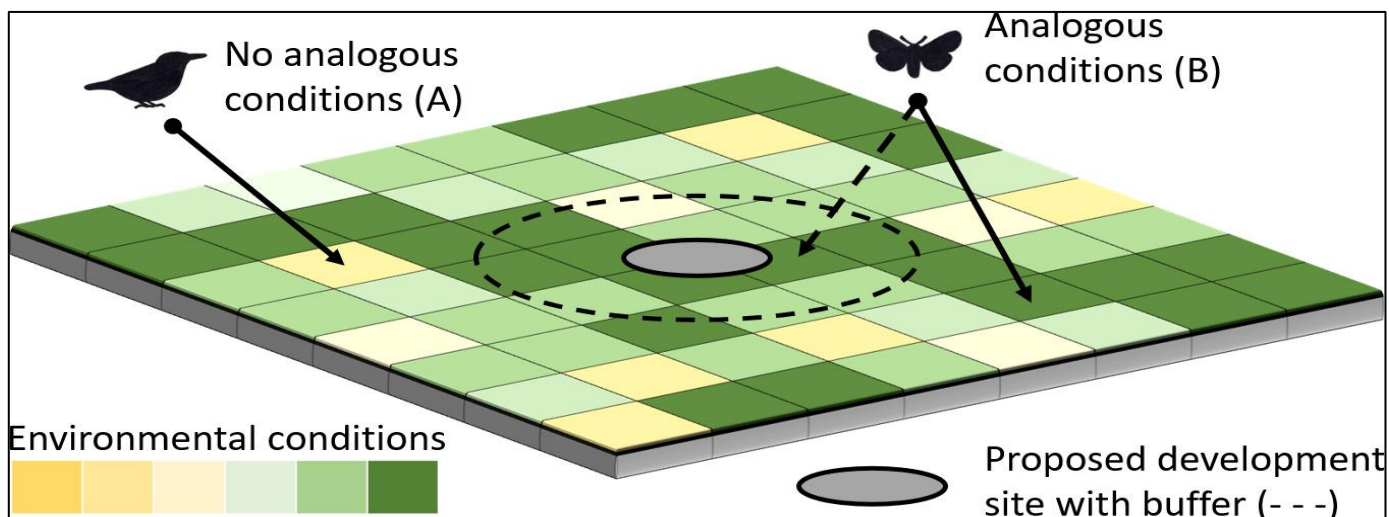


Figure 4 Assessing Habitat Suitability Through Environmental Analogs in Development Planning (Baker, et. al 2021)

Figure 4 Illustrates how environmental analogs are used to assess habitat suitability in the context of proposed land development. It shows a grid representing varying environmental conditions, with a central development site and its surrounding buffer zone. Species such as the bird (A) face habitat loss when no analogous environmental conditions exist nearby, hindering relocation or survival. In contrast, species like the butterfly (B) benefit from the presence of analogous environmental conditions within reachable distance, enabling them to potentially relocate and adapt. This approach highlights the importance of evaluating spatial environmental similarity when planning developments, as it influences species resilience and ecosystem sustainability. The integration of remote sensing data with SDMs has proven effective in capturing the dynamic changes in habitat suitability over time. By utilizing time-series satellite imagery, researchers can monitor changes in vegetation cover and other ecological indicators before and after volcanic events. This temporal analysis allows for the assessment of recovery trajectories and the identification of areas requiring targeted conservation efforts. Furthermore, the incorporation of climate change scenarios into SDMs provides insights into the potential long-term effects of volcanic eruptions on species distributions. By modeling future climatic conditions, these models can predict shifts in suitable habitats and inform proactive conservation planning. In conclusion, the application of SDMs, enhanced by remote sensing data and climate projections, offers a robust framework for evaluating habitat impacts and predicting species distribution changes following volcanic eruptions. This integrated approach supports informed decision-making in biodiversity conservation and ecosystem management.

➤ Validation and Ground-Truthing Strategy

The validation and ground-truthing of remote sensing-based habitat impact assessments and species distribution models (SDMs) are pivotal for ensuring the accuracy and reliability of ecological predictions. Ground-truthing involves the collection of field data to verify and refine remote sensing outputs, thereby enhancing model performance and supporting informed conservation decisions. Traditional ground-truthing methods, while effective, can be resource-intensive and limited in spatial coverage. Recent advancements have introduced innovative strategies to address these challenges. One such advancement is the integration of drone technology with remote sensing data. Drones equipped with high-resolution imaging sensors facilitate the rapid collection of detailed spatial data, enabling the creation of comprehensive ground-truth datasets. For instance, a study demonstrated that combining drone-based ground truthing with remote sensing time series data improved the accuracy of vegetation mapping, achieving a classification accuracy of 92.59%. This approach allows for efficient and scalable validation across complex landscapes. Additionally, the application of spatially balanced sampling techniques has been shown to enhance the representativeness of ground-truth data. By systematically selecting sampling locations that cover the full range of environmental variability, researchers can reduce spatial bias and improve model generalization. This methodology has been effectively utilized in various ecological studies to refine habitat models and ensure their applicability across diverse terrains. The incorporation of citizen science data further enriches ground-truthing efforts. Platforms like eBird provide extensive species occurrence records that can be integrated with remote sensing data to validate SDMs. A study leveraging such data demonstrated

the feasibility of mapping bird species distributions using satellite imagery and citizen science observations, thereby enhancing the spatial resolution and accuracy of ecological models. Moreover, advancements in model evaluation techniques, such as spatial cross-validation and spatio-temporal validation, have been developed to assess the robustness of SDMs. These methods account for spatial autocorrelation and temporal dynamics, providing more reliable estimates of model performance and ensuring that predictions are not overfitted to specific locations or time periods. The integration of innovative ground-truthing strategies, including drone technology, spatially balanced sampling, citizen science data, and advanced validation techniques, significantly enhances the accuracy and reliability of remote sensing-based habitat impact assessments and species distribution models. These advancements facilitate more effective monitoring and conservation of biodiversity in the face of environmental changes.

IV. RESULTS AND DISCUSSION

➤ Remote Sensing Analysis of Volcanic Events

Remote sensing technologies have become indispensable tools in the analysis and monitoring of volcanic events, offering critical insights into eruption dynamics and their environmental impacts. These technologies enable the observation of volcanic activity in near real-time, providing data that are essential for hazard assessment, early warning systems, and post-eruption recovery efforts. Satellite-based remote sensing platforms, such as the European Space Agency's Sentinel missions and NASA's MODIS (Moderate Resolution Imaging Spectroradiometer), are pivotal in volcanic monitoring. Sentinel-1's Synthetic Aperture Radar (SAR) capabilities allow for the detection of ground deformations associated with volcanic activity, while Sentinel-2 provides multispectral imagery that aids in assessing vegetation health and land cover changes.

Table 5 Remote Sensing-Driven Assessment of Volcanic Activity and Its Ecological Impacts on Forest Reserves

Component	Technology/Platform	Functionality	Key Output	Application in Volcanic Monitoring
Ground Deformation Detection	Sentinel-1 SAR + InSAR	Measures surface displacement due to magma movement	Deformation maps, subsidence/uplift indicators	Early warning of eruption and ground instability
Vegetation & Land Cover Change	Sentinel-2 Multispectral Imagery	Tracks vegetation health and land cover variation	NDVI maps, deforestation overlays	Assessment of ecological impact and forest recovery
Thermal Anomaly Identification	MODIS (Terra/Aqua), VIIRS (Suomi NPP)	Detects heat signatures and active lava flows	Hotspot detection, temperature anomaly maps	Real-time lava tracking and thermal hazard monitoring
Spatial Impact Assessment	GIS (Geographic Information Systems)	Integrates multiple datasets for spatial analysis	Forest impact zones, overlay maps with protected areas	Identifying at-risk regions and planning conservation actions
Automated Feature Recognition	Machine Learning (e.g., Deep Learning Models)	Analyzes satellite data for pattern recognition and classification	Automated lava flow and land change detection	Accelerated and accurate mapping for rapid response

Table 5 Highlights the components of a remote sensing-based system used for analyzing volcanic events and their ecological consequences. Sentinel-1 SAR is used to detect ground movement, while Sentinel-2 provides multispectral imagery to assess vegetation and land cover changes. MODIS and VIIRS thermal sensors highlight areas of elevated temperature, helping identify active lava flows. GIS platforms integrate these datasets to visualize the spatial extent of volcanic impacts, particularly on forest reserves. Additionally, machine learning algorithms automate the analysis of satellite imagery, detecting features like lava paths and land cover changes more efficiently. Together, these technologies support continuous monitoring, early warning systems, and post-eruption environmental assessments. MODIS, on the other hand, offers thermal infrared data that are instrumental in identifying thermal anomalies and active lava flows during eruptions. These datasets facilitate the continuous monitoring of volcanic regions, even in remote or hazardous areas where ground-based observations may be

limited. In addition to optical and radar satellite imagery, thermal infrared data play a crucial role in detecting volcanic hotspots and assessing thermal anomalies. The Moderate Resolution Imaging Spectroradiometer (MODIS) aboard NASA's Terra and Aqua satellites, along with the Visible Infrared Imaging Radiometer Suite (VIIRS) on the Suomi NPP satellite, offer thermal infrared observations that are instrumental in identifying active lava flows and elevated surface temperatures. These thermal signatures are indicative of ongoing volcanic activity and are essential for real-time monitoring and hazard assessment. Geospatial information systems (GIS) serve as powerful tools for integrating and analyzing multi-source remote sensing data. By overlaying volcanic activity data with forest reserve boundaries and vegetation maps, GIS platforms enable the assessment of the spatial extent of volcanic impacts on forest ecosystems. This integration allows for the identification of areas within forest reserves that are most vulnerable to volcanic disturbances and informs targeted conservation and

restoration efforts. Furthermore, the application of machine learning algorithms enhances the analysis of remote sensing data by automating the classification of land cover types and detecting changes in vegetation. These algorithms can process large volumes of satellite imagery to identify patterns and anomalies that may indicate volcanic activity or its impacts on forest reserves. For instance, deep learning models have been employed to analyze high-resolution satellite imagery, facilitating the identification of lava flows and other volcanic features with high accuracy. In conclusion, the integration of remote sensing technologies provides a comprehensive approach to monitoring volcanic eruptions and their impacts on forest reserves. By combining satellite imagery, thermal data, GIS analysis, and machine learning techniques, researchers and conservationists can effectively assess and mitigate the ecological consequences of volcanic activity, thereby contributing to the preservation of biodiversity in forested regions.

➤ Spatiotemporal Patterns of Habitat Disruption

The spatiotemporal analysis of habitat disruption, particularly in regions affected by volcanic activity, is essential for understanding the dynamics of ecosystem changes and informing conservation strategies. Remote sensing technologies, such as satellite imagery and thermal infrared sensors, have proven invaluable in monitoring these changes over time. For instance, a study by Zhang et al. (2024) utilized Landsat and Sentinel-2 imagery to assess forest disturbances in temperate regions of Northern China from 1985 to 2020. The LandTrendr algorithm was employed to detect disturbances, revealing significant impacts from extreme climate events and droughts, with over one-third of both planted and natural forests experiencing substantial disturbance during these period. This highlights the importance of high-resolution temporal data in capturing the nuances of habitat disruption. Similarly, research by Turner et al. (2023) examined the spatiotemporal dynamics of land use and land cover changes around Volcanoes National Park.

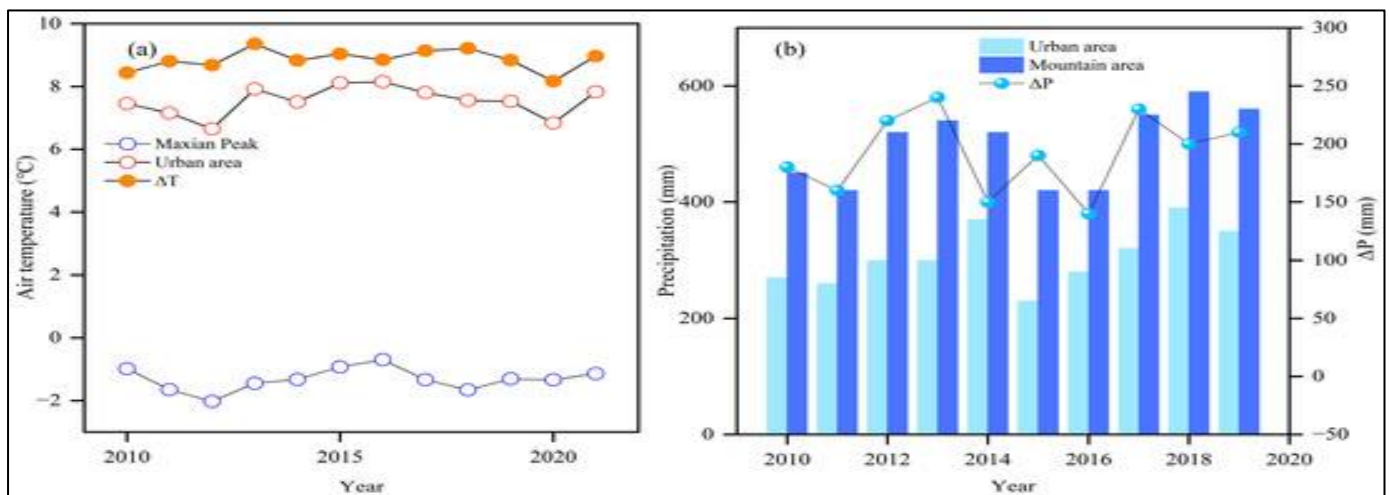


Fig 5 Spatiotemporal Variations in Climate Parameters Across Urban and Mountain Environments (2010–2020) (MDPI, 2025)

Figure 5 illustrates spatiotemporal variations in air temperature and precipitation between urban and mountain regions from 2010 to 2020. Panel (a) shows that urban areas consistently experienced higher average temperatures compared to the mountain region (Maxian Peak), with a notable and persistent temperature differential (ΔT) throughout the observed period. Panel (b) highlights annual precipitation trends, where urban areas generally received less precipitation than mountain areas, and the differences in precipitation (ΔP) fluctuated significantly across years. These spatiotemporal patterns underscore the contrasting microclimatic conditions influenced by elevation and urbanization, offering insights into regional climate dynamics and the potential impacts of urban heat island effects and orographic precipitation. The study employed multi-temporal satellite data to analyze the expansion of agricultural activities and urbanization, which led to habitat fragmentation and degradation, posing threats to biodiversity. This underscores the role of human activities in exacerbating habitat disruption in volcanic regions. In the context of volcanic activity, a study by Calvache and Rueda (2023) focused on the Andes region, where volcanic eruptions

have historically impacted forest ecosystems. Using remote sensing data, they assessed the extent of forest cover loss and the subsequent recovery phases, providing insights into the resilience of these ecosystems to volcanic disturbances. Furthermore, research by Vidal et al. (2024) employed remote sensing technologies to map and model lava flows from Mount Merapi. By analyzing the spatiotemporal patterns of lava flow paths and their interaction with surrounding vegetation, the study contributed to understanding the immediate and long-term impacts of volcanic eruptions on forest habitats. A study by Biggs and Walker (2024) utilized InSAR and satellite imagery to monitor ground deformation associated with volcanic activity at Mount Etna. The analysis provided insights into the spatial distribution of volcanic hazards and their potential effects on surrounding habitats, emphasizing the need for integrated monitoring approaches in volcanic regions.

➤ Endemic Species Vulnerability and Response Patterns

Endemic species, particularly those inhabiting volcanic regions, exhibit unique vulnerabilities and adaptive responses to environmental disturbances such as

volcanic eruptions. These species often have specialized habitat requirements and limited distributions, making them particularly susceptible to habitat alterations and climatic changes induced by volcanic activities. Recent studies have utilized remote sensing technologies to monitor the impacts of volcanic events on endemic species. For instance, the 2021 Tajogaite eruption on La Palma in the Canary Islands provided an opportunity to assess the effects of volcanic gas emissions and tephra deposition on the endemic Canary pine (*Pinus canariensis*). Combining in-situ monitoring with remote sensing data, researchers observed that while the eruption caused chlorotic damage up to approximately 7 km around the crater, the species exhibited resilience through widespread resprouting, indicating an adaptive response to volcanic disturbances. Similarly, the 2021 Cumbre Vieja eruption in the Canary Islands prompted investigations

into the interactions between volcanic eruptions and previous wildfires on seedling establishment in Canary pine forests. The study found that areas affected by prior wildfires exhibited diminished seedling densities compared to areas impacted solely by the volcanic eruption, suggesting that fire history negatively influenced seedling establishment and highlighting the compounded effects of multiple disturbances on endemic species. Species distribution models (SDMs) have also been employed to predict the potential and realized distributions of endemic species in response to environmental changes. For example, a study estimated the distribution of the semi-fossorial snake *Atractus lasallei*, endemic to northwestern Colombia, using SDMs to understand its habitat preferences and potential responses to environmental changes.

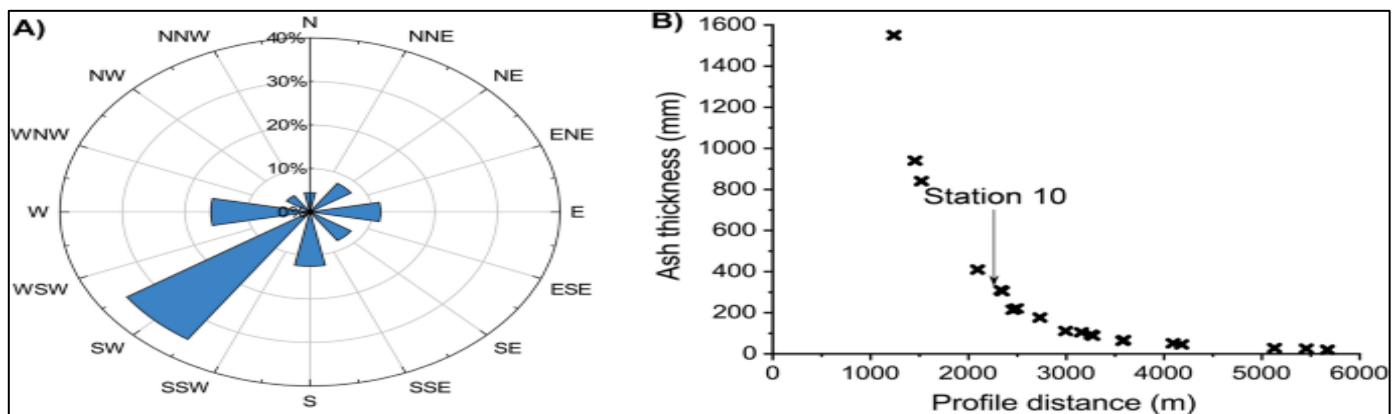


Fig 6 Impacts of Volcanic Eruptions on Endemic Species Distribution and Ash Dispersion Dynamics (Nogales, et. al 2022)

Figure 6 Highlights the dual focus of the study: understanding how volcanic activity affects both the spatial patterns of species that are uniquely adapted to specific ecosystems (endemic species) and the distribution of volcanic ash across the landscape. Volcanic eruptions can drastically alter habitats, disrupt ecological balance, and threaten the survival of endemic flora and fauna, especially those with limited geographic ranges. Simultaneously, the study examines how wind direction and distance influence ash fallout, which can further degrade ecosystems by altering soil chemistry, vegetation cover, and water availability. This integrated approach provides insight into the cascading ecological impacts of eruptions, particularly in biodiversity hotspots where endemic species are most vulnerable. Furthermore, the global overlap between species distributions and occurrences of natural hazards, including volcanic eruptions, has been assessed to understand the risks faced by endemic species. The study revealed that a significant proportion of terrestrial vertebrates, including birds, mammals, amphibians, and reptiles, are at risk due to at least one natural hazard, with many species found in tropical and island regions where endemic species are prevalent. Remote sensing technologies, coupled with species distribution models, provide valuable tools for monitoring and understanding the vulnerabilities and adaptive responses of endemic species to volcanic

disturbances. These approaches facilitate informed conservation strategies aimed at mitigating the impacts of volcanic activities on biodiversity.

➤ Evaluation of the Integrated Framework

The integrated framework combining remote sensing (RS) and geographic information systems (GIS) has emerged as a pivotal tool in ecological monitoring, particularly in assessing habitat quality and biodiversity. This approach leverages high-resolution satellite imagery, advanced spatial analysis, and ecological modeling to provide comprehensive insights into environmental changes. Recent advancements underscore the efficacy of this integrated framework in various ecological contexts. For instance, the application of the Remote Sensing Ecological Index (RSEI) model has facilitated large-scale, rapid assessments of ecological environment quality, enhancing our understanding of habitat conditions and informing conservation strategies. Furthermore, the integration of ground-based and remote sensing data with deep learning techniques has shown promise in mapping forest habitats and observing ecological changes, highlighting the potential of combining traditional and modern data sources for more accurate assessments. The utility of this integrated approach is further exemplified in the context of wetland ecosystems.

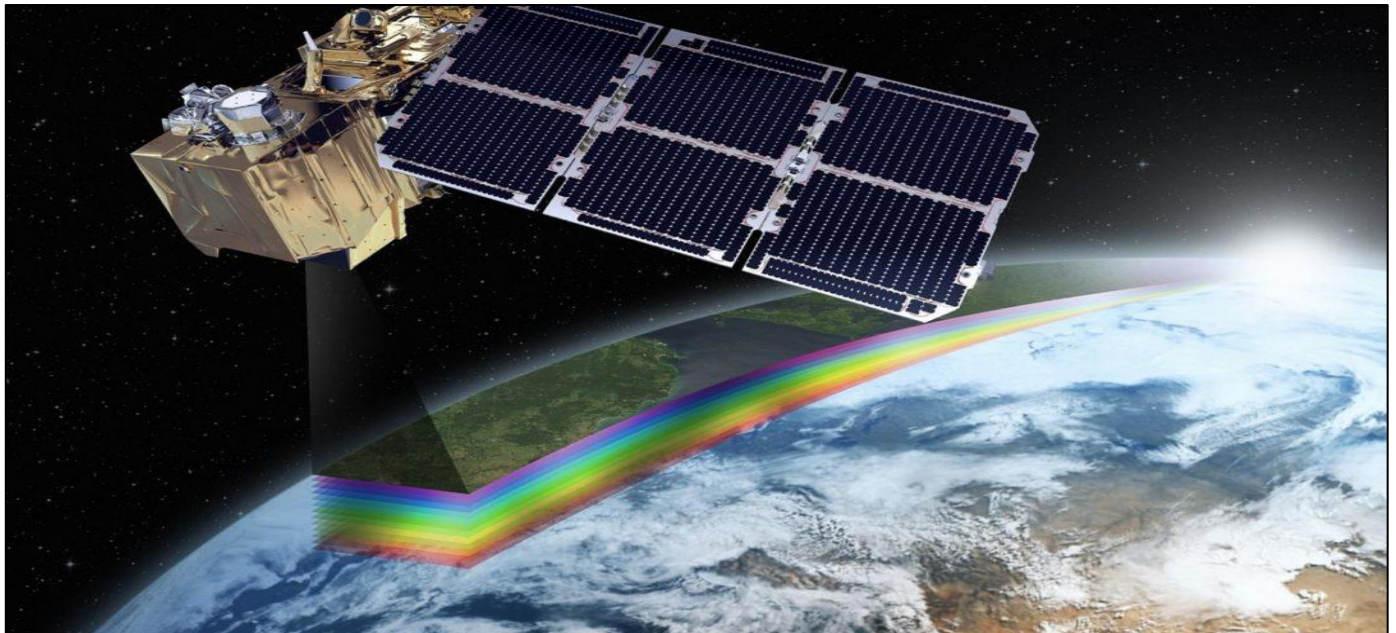


Figure 7 Remote Sensing and GIS: Mapping Earth Through Satellite Spectral Imaging (Cervest 2020, March 13).

Figure 7 Explores how satellite-based remote sensing technologies capture data across various spectral bands to observe and monitor Earth's surface. By integrating this data with Geographic Information Systems (GIS), scientists and decision-makers can analyze spatial patterns, track environmental changes, assess land use, and support disaster management. This synergy between remote sensing and GIS enhances our ability to visualize, interpret, and manage complex geographical information at local, regional, and global scales. A study formulated an integrated framework for assessing wetland ecosystem health, utilizing remotely sensed data and geospatial techniques to evaluate the impacts of land use/cover changes and landscape patterns on habitat fragmentation. This comprehensive approach provided valuable insights into ecosystem structure, function, and resilience, underscoring the framework's applicability in diverse ecological settings. Moreover, the application of GIS-based multi-criteria evaluation frameworks has been instrumental in assessing the environmental and biodiversity impacts of intermodal transport routes. By integrating ecological considerations into transport planning, these frameworks have enabled the identification of routes that balance operational efficiency with ecological preservation, demonstrating the versatility of the integrated RS-GIS approach in addressing complex environmental challenges. The integrated RS-GIS framework has proven to be a robust and adaptable tool in ecological monitoring and assessment. Its application across various ecosystems and environmental contexts highlights its capacity to provide detailed, spatially explicit insights into habitat conditions and biodiversity, thereby informing effective conservation and management strategies.

➤ *Implications for Conservation and Disaster Management*

The integration of remote sensing and geographic information systems (GIS) has significantly enhanced the capacity for conservation and disaster management,

particularly in regions susceptible to volcanic activities. These technologies facilitate real-time monitoring, risk assessment, and informed decision-making, thereby improving the resilience of ecosystems and communities. In conservation, remote sensing enables the continuous monitoring of habitat changes, allowing for the early detection of disturbances such as volcanic eruptions. For instance, the application of satellite-based flood mapping in Thailand demonstrated how remote sensing can assess the socioeconomic impacts of natural disasters, providing valuable data for conservation planning and response strategies. Similarly, the development of a new remote sensing method by the UConn Global Environmental Remote Sensing Lab to monitor primary forest loss exemplifies how these technologies can track environmental changes and inform conservation efforts. In disaster management, the use of remote sensing and GIS has proven instrumental in enhancing preparedness and response to volcanic hazards. The U.S. Geological Survey's Volcano Hazards Program utilizes these technologies to deliver forecasts, warnings, and information about volcanic hazards, thereby minimizing social and economic disruptions. Furthermore, the integration of machine learning models with remote sensing data has been proposed as a novel approach to disaster management, enabling the analysis of biodiversity protection and forest resources during volcanic events. Moreover, the Group on Earth Observations (GEO) Work Programme emphasizes the development and optimization of remote sensing-based monitoring and early forecasting programmes for habitat monitoring and risk assessment, underscoring the importance of these technologies in managing natural hazards. The integration of remote sensing and GIS technologies plays a crucial role in enhancing conservation efforts and disaster management strategies. By providing accurate, timely data, these tools support the protection of biodiversity and the mitigation of risks associated with volcanic activities, thereby contributing to the resilience of both ecosystems and human communities.

V. CONCLUSION AND RECOMMENDATION

➤ *Summary of Key Insights*

The integration of remote sensing technologies and Geographic Information Systems (GIS) for monitoring volcanic eruptions and their ecological impacts has proven to be an effective approach for assessing habitat disruption and species vulnerability. This research highlights the critical role of high-resolution satellite imagery, thermal infrared sensors, and UAVs in providing real-time data on volcanic activity and its effects on forest ecosystems. These technologies enable the continuous monitoring of land cover changes, lava flows, and vegetation health, which are essential for understanding the full scope of volcanic disturbances. Additionally, the study underscores the importance of combining remote sensing data with ecological models, such as species distribution models (SDMs), to predict potential shifts in species habitats and to assess post-eruption recovery. By integrating time-series data, remote sensing allows for the assessment of both immediate and long-term effects on biodiversity, providing valuable insights into species resilience and habitat restoration potential. Furthermore, the research highlights the necessity of accurate data acquisition and preprocessing methods, including radiometric calibration, geometric correction, and noise reduction, to ensure the quality and reliability of remote sensing outputs. The application of machine learning and deep learning models further enhances the accuracy of volcanic activity mapping and species distribution predictions, offering more precise tools for conservation planning. In conclusion, the integrated use of remote sensing and GIS technologies not only advances our understanding of volcanic impacts on ecosystems but also offers robust solutions for conservation and disaster management. These tools provide critical data for mitigating the ecological consequences of volcanic eruptions, enabling more informed and proactive conservation strategies that support ecosystem resilience and biodiversity protection.

➤ *Strategic Recommendations*

Based on the findings of this study, several strategic recommendations emerge for enhancing the monitoring of volcanic impacts on ecosystems and improving conservation and disaster management efforts. Firstly, it is crucial to continue advancing the integration of remote sensing data with ecological models and GIS platforms. This integration allows for a more comprehensive understanding of volcanic activity's spatiotemporal effects on habitats, facilitating early warnings and more effective disaster response. Expanding the use of high-resolution satellite imagery and UAVs, particularly for real-time monitoring, will greatly improve our ability to detect changes in vegetation health, land cover, and volcanic hazards with greater accuracy. Secondly, strengthening the use of machine learning and artificial intelligence techniques in processing and analyzing remote sensing data will be essential for enhancing the precision of species distribution models and habitat impact assessments. These technologies enable the automatic classification and detection of environmental changes, providing timely and actionable insights for conservationists and disaster

managers. Furthermore, machine learning algorithms can improve the prediction of species habitat shifts and recovery patterns, enabling more proactive conservation efforts. Thirdly, incorporating ground-based validation and citizen science data is vital for enhancing the reliability of remote sensing outputs. Ground-truthing remains an indispensable component of habitat monitoring, and leveraging local knowledge through citizen science initiatives can provide additional, valuable data for validating remote sensing results and improving ecological models. This collaborative approach can help fill data gaps in remote and inaccessible areas, providing more robust assessments of volcanic impacts. Lastly, fostering collaboration between governments, researchers, and local communities is essential for the effective implementation of these technologies in conservation and disaster management. Governments should prioritize the allocation of resources for capacity building in remote sensing and GIS technologies for local conservation teams. Additionally, policies supporting the use of open-access satellite data and collaborative data-sharing platforms will enhance global efforts in biodiversity conservation and disaster preparedness. In conclusion, a multi-faceted approach combining advanced technologies, machine learning, local engagement, and inter-agency collaboration will significantly improve volcanic impact assessments and contribute to more effective conservation and disaster management strategies. These recommendations aim to enhance ecosystem resilience, safeguard biodiversity, and mitigate the risks posed by volcanic events.

➤ *Future Research Directions*

Future research in the field of volcanic impact monitoring and habitat conservation should focus on several key areas to enhance the effectiveness of remote sensing and GIS technologies. One crucial direction is the refinement of species distribution models (SDMs) by integrating more diverse datasets, including climate models, species behavior data, and finer spatial resolution satellite imagery. This would allow for more accurate predictions of species' responses to volcanic disturbances, particularly in dynamic ecosystems where environmental conditions change rapidly. The inclusion of high-resolution temporal data will also enable a deeper understanding of recovery dynamics, helping conservationists to predict long-term species responses and plan for ecosystem restoration more effectively. Another promising research avenue is the integration of multi-sensor data fusion techniques. Combining data from various platforms, such as optical imagery, synthetic aperture radar (SAR), and thermal infrared sensors, could significantly improve the detection and monitoring of subtle environmental changes associated with volcanic activity. Multi-sensor fusion could enhance the spatial and temporal resolution of volcanic hazard mapping, providing more accurate and timely assessments of habitat disruptions. Exploring the potential of real-time data integration for disaster response and recovery will also be an important focus, ensuring that conservation efforts can be adapted swiftly in response to ongoing volcanic events. Furthermore, advancing machine learning and artificial

intelligence (AI) models to automate the analysis of remote sensing data could reduce the time required for post-eruption assessments and habitat impact mapping. Research should focus on developing AI algorithms capable of identifying and predicting shifts in species habitat suitability based on dynamic environmental conditions, such as lava flow paths, ash deposition, and vegetation loss. This will further enhance the speed and accuracy of impact assessments, enabling quicker decision-making for conservationists. Additionally, investigating the potential of citizen science and crowdsourced data in enhancing volcanic monitoring efforts is another promising direction. Engaging local communities in the collection of ground truth data and ecosystem observations during volcanic events will complement remote sensing efforts, filling gaps in data from remote or difficult-to-access areas. Collaborative platforms for data sharing and analysis should be developed to allow the integration of citizen-collected data into the broader monitoring framework. Lastly, research should explore the broader implications of volcanic disturbances on ecosystem services, including their impact on water quality, soil fertility, and carbon storage. Understanding these broader ecological consequences will improve the assessment of volcanic hazards and guide more comprehensive conservation strategies that address both biodiversity and ecosystem service preservation. In conclusion, future research should prioritize the integration of diverse data sources, the refinement of predictive models, and the incorporation of real-time monitoring technologies. By advancing these areas, researchers will be better equipped to mitigate the ecological impacts of volcanic disturbances, enhance ecosystem resilience, and safeguard biodiversity in the face of natural hazards.

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