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Research Article

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Prediction in Terrestrial and Aquatic Ecosystems Using Sentinel-2, Landsat 8, and MODIS Data: An Integrated Approach through Google Earth Engine

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Abstract In this study, we analyzed drought and vegetation dynamics in Taiwan by combining satellite observations from Sentinel-2, Landsat 8, and MODIS. The focus was on both terrestrial and aquatic ecosystems, as well as agricultural areas, for the period 2017 to 2023. Using the Google Earth Engine (GEE), we calculated key indices including NDVI, VCI, NDWI, and derived vegetation condition metrics to assess drought severity. VCI was computed monthly based on historical NDVI values and categorized into five drought severity classes to capture relative vegetation stress. Each satellite contributed uniquely to the analysis: Sentinel-2 provided high-resolution data for fine-scale monitoring, Landsat 8 offered continuity over the medium term, and MODIS supplied long-term and frequent observations, allowing both local and regional perspectives on vegetation and drought patterns. Limited ground-based measurements confirmed that satellite-derived results were consistent with precipitation records from CHIRPS, supporting the reliability of the data. The results were presented through maps, time series plots, and dynamic graphs, highlighting both seasonal fluctuations and interannual variability in drought and vegetation conditions. By combining spatially and temporally diverse datasets, the better coverage and continuity of monitoring enhanced the capability to accurately monitor ecosystem health and vegetation dynamics. In general, this method provides useful information on the benefits of integrating multi-source satellite observations for sustainable ecosystem management. Our research offers scientific support for early warning system creation and pertinent ecosystem protection and resource management by way of a thorough understanding of both the drought dynamics/synchrony and vegetative responses.

Keywords normalized difference vegetation index (NDVI) · Vegetation Condition Index (VCI) · Google Earth Engine (GEE) · ecosystems

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Introduction

The NDVI, used to assess the density and health of the vegetation, is calculated from near-infrared and red. Thus, reflectance ratios of near-infrared and Red to total reflect a better picture of vegetative intensity and geographic variation. It has been frequently used in various crop yield estimate, land cover classification, phenology monitoring, drought study, and environmental change detection, among other purposes. (Wang 2020; Lyle Ghorbanian et al., 2022; Mashhadi et al., 2022; Liu et al., 2022; Guo et al., 2021; Aksoy et al., 2021; Huang et al., 2023; Al., 2023; Feng et al., 2022). Thus, its capacity to provide precise data across time and space has turned it into a crucial tool for resource management and environmental monitoring.

Using time series of NDVI based from MODIS, Landsat 8, and Sentinel-2 data helps greatly to track long-term changes in vegetation and seasonal dynamics. For this collection, however, whether the clouds hid earth from space, varying sensor resolutions, and temporal gaps all could produce the difference between one year to another one (Ma et al., 2022; Cao et al., 2022; Yang et al., 2022; Xiong et al., 2022). Dealing with Cloud masking, temporal interpolation, and inter-sensor calibration are among the preprocessing methods required to ensure data integrity and continuity in plant monitoring.

Another often used index apart from NDVI is vegetation condition indicators (VCI), typically used for drought monitoring. VCI is a relative index of vegetation stress or drought severity (Zambrano et al., 2016) adjusted for the range of historic NDVI values. Thus, VCI is especially helpful for areas with little meteorological data to early detect plant responses to water shortages. The VCI more effectively represents vegetation stress brought on by drought than does the cumulatice NDVI, therefore allowing it to be an early warning system indicator.

Taiwan is especially interesting for such study because of its diverse terrain, flora, and range of temperatures. On the island, monsoon weather, typhonic events, and human activities often disrupt the ecosystems. Preserving water supplies, upholding ecosystems' integrity, and guaranteeing agricultural output under such conditions all depend on accurate and fast monitoring of drought. productivity. Adding plants, water, and atmosphere in the system improves the thoroughness of any integrated monitoring plan and helps to enable adaptive management techniques in ecologically fragile areas.

Especially in areas with few ground-truth observations, remote sensing provides a strong and spatially wide instrument for drought detection. A variety of satellite-derived drought indices have been developed, which focus on vegetation condition (e.g., NDVI, VCI), surface temperature anomalies, and moisture availability. Previous research has shown their performance in identifying drought commencement, length and intensity on a wide variety of natural ecosystems (Gu et al., 2007; Mishra et al., 2015; Rhee et al., 2010; Wu et al., 2013; Kogan et al., 1995; Domenikiotis et al., 2004; Kuri et al., 2014; Liu et al., 2002; Seiler et al., 1998; Shen et al., 2014; Singh et al., 2003; Wan, 2001). Among these, NDVI- and VCI-based indices have been widely used to map drought-affected areas, identify vulnerable vegetation, and support evidence-based policymaking.

The development of cloud computing platforms (e.g., Google Earth Engine, GEE) has strengthened the infrastructure for large-scale drought investigations. GEE allows processing of multi-sensor satellite imagery in near real time and smooth data integration. Through fusing the three remote sensing sensors Sentinel-2, Landsat 8 and MODIS, researchers are able to construct a multi-resolution multi-temporal structure as an effective tool for drought monitoring. Sentinel-2 fine spatial resolution permits detailed analysis, Landsat 8 provides long-term continuity and MODIS allows for frequent observations so that a more complete assessment of ecosystem stress and its drivers can be made.

Building on this framework, the present study assesses drought conditions in Taiwan's terrestrial and aquatic ecosystems from 2017 to 2023. NDVI, VCI, and NDWI indices derived from Sentinel-2, Landsat 8, and MODIS were analyzed within GEE. The study includes multi-sensor comparisons, seasonal and annual drought mapping, and correlation with CHIRPS precipitation data. NDWI is specifically used to capture aquatic ecosystem dynamics, addressing a gap in previous studies where water-related drought monitoring was limited.

A limited ground-based validation was performed, the severity of drought was graded for various land cover types (such as forests and agricultural areas) which provides ecosystemrelated information that increases confidence. Through maps, histograms and time-series graphs showing spatially explicit drought indices the study provides a detailed view on how the dynamics of drought is described in space over time. Cumulatively, these results provide important guidelines to support sustainable ecosystem management, inform drought reduction policies at a local scale and propose a methodological framework applicable in other regions characterized by pressing environmental concerns.

Materials and Methods

Study area

This study focuses on drought prediction in the terrestrial and aquatic ecosystems of Taiwan. Located in Southeast Asia, Taiwan experiences both tropical and subtropical climate conditions. The island's varied topography and microclimatic features foster rich ecosystem diversity, while at the same time making the impacts of environmental stressors, such as drought, more complex.

Taiwan lies between 23°–25° north latitude and 120°–122° east longitude, covering an area of about 36,000 km². Its geography—coastal plains, valleys, and vast mountain ranges—all influence ecosystem processes and their dynamics. The northern and high-altitude areas are often colder and more humid, while the southern and coastal areas are often hotter and drier, so the climate also varies across the island. Droughts therefore range in severity and influence throughout regions, not equally. Figure 1 shows the study area's position.

Tropical forests, subtropical shrublands, mountain forests, and coastal systems are among the various ecosystems supported on the island. Furthermore important for sustaining biodiversity and promoting agriculture, its rivers, lakes, and wetlands help. Essential for human use and ecological stability, these freshwater resources are very vulnerable to droughts.

Taiwan is facing growing environmental pressures like climate change, rapid urbanization, and intensive agriculture. These pressures increase the risks linked to ecosystem stress, especially drought. In recent years, the frequency and severity of drought events have both risen. This trend creates challenges for water management and agricultural productivity.

Given these conditions, effective monitoring and predicting drought are critical for protecting ecosystem health and ensuring sustainable water use. This study aims to tackle these challenges by developing a combined method for drought prediction that considers Taiwan's varied ecosystems and complex environmental conditions.

Materials

Remote sensing data and geospatial methods were used to evaluate how drought affects vegetation in Taiwan's land and water ecosystems. The selection of data sources and analysis platforms aimed to support the space flight, time sequence, and spectral measurements. This approach offers a wide range of trustworthiness in our results.

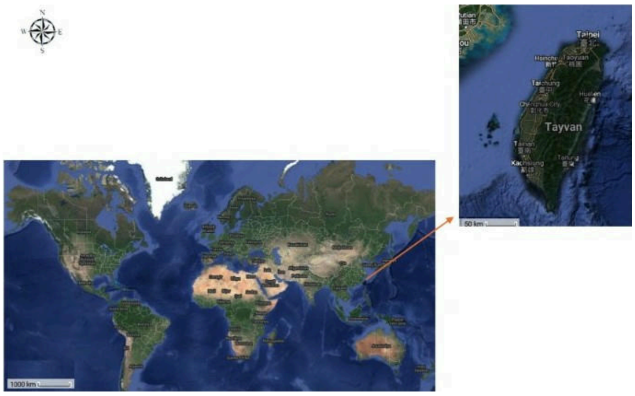

Figure 1. Location of study area

Analysis of vegetation was conducted using high-resolution (10 m) spatial satellite imagery and this formed the basis of the data I used. The red (B4) and near-infrared (B8) bands were specifically used to derive both Normalized Difference Vegetation Index (NDVI) as well as the Vegetation Condition Index (VCI), which are crucial in monitoring vegetation vigor and stress.

Landsat 8 images were included to expand the time span and identify long-term drought trends. With a 30 m resolution and similar spectral bands to Sentinel-2, the NDVI values were consistently computed over different years.

MODIS had a lower resolution but provided many observations that were useful for tracking larger patterns. In addition to vegetation statistics and indexes, MODIS aerosol products, like the Optical_Depth_047 band, were examined to understand the atmospheric effects, such as haze or pollution, on vegetation health.

To support vegetation monitoring, the Normalized Difference Water Index (NDWI) was calculated using the green (B3) and near-infrared (B8) bands of Sentinel-2. NDWI allowed quantifying water availability and aquatic vegetation condition, thus explaining both dual land and water ecosystem focus of this study.

All datasets were analysed on the Google Earth Engine (GEE) platform, which allowed for large-scale time-series analysis, index generation and classification/mapping. Geographic Information Systems (GIS) software was additionally employed for visualization, spatial statistics, and post-processing.

Integration of these datasets and models resulted in high-resolution vegetation health indices, drought severity maps (exponentially weighted SPI), time series plots, and statistical products, providing a sound approach for ecological drought analysis in Taiwan.

Methodology

This study was designed to monitor and predict drought severity in Taiwan from 2017 to 2023 using multi-sensor remote sensing data integrated within the Google Earth Engine (GEE) environment. The methodological framework (illustrated in Fig. 2) consists of four main stages: data acquisition, index computation, classification, and spatial-temporal analysis.

Study Area and Timeframe

Taiwan was selected as the study area due to its diverse topography, ecosystem types, and vulnerability to climate-induced droughts. Administrative boundaries were extracted using the FAO GAUL Level-0 dataset. The analysis spanned a seven-year period (2017–2023) to evaluate interannual and seasonal variability in vegetation health and water stress.

Index Calculations (NDVI, VCI, NDWI)

NDVI was calculated using Sentinel-2's B8 and B4 bands as:

NDVI = (B8 - B4) / (B8 + B4)

VCI was derived using the NDVI time series on a per-pixel basis as:

VCI = (NDVI_current - NDVI_min) / (NDVI_max - NDVI_min) × 100

NDVI_min and NDVI_max were computed as the minimum and maximum values observed per pixel over the entire study period (2017–2023).

Annual mean NDVI and VCI values were calculated for each year to assess vegetation anomalies and classify drought intensity.

NDWI was computed using Sentinel-2's B3 (Green) and B8 (NIR) bands:

NDWI = (B3 - B8) / (B3 + B8)

This index was used to assess water stress and aquatic vegetation variation, contributing to the study's aquatic ecosystem monitoring.

Temporal Analysis and Area Estimation

Time series of NDVI and VCI were analyzed annually. The mode of VCI classes was also calculated to identify the most frequent drought level per pixel. The pixel area (based on 10m or 30m resolution depending on the source) was used to quantify the total area affected under each drought class. These results were summarized in tables and visualized through bar and line graphs.

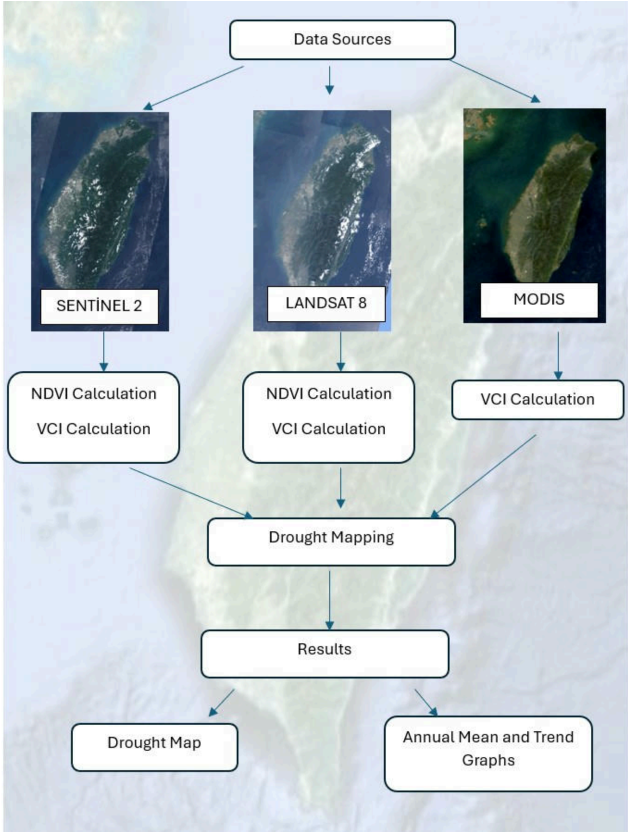

Figure 2. Workflow in the study

Data Integration and Validation

To ensure robustness, Sentinel-2, Landsat 8, and MODIS data were cross-validated for consistency in NDVI values. Preliminary comparison with CHIRPS precipitation data was performed to assess correlation between VCI and rainfall variability. Although limited, ground-truthing was attempted using publicly available vegetation observation data and regional reports.

Tools

All image preprocessing (cloud masking, clipping, temporal filtering) and index computations were performed in GEE using JavaScript API.

Visualization and final map production were completed in QGIS.

Statistical graphs were created using SPSS and Excel.

This integrated and repeatable methodology facilitates large-scale drought monitoring and supports early-warning efforts by providing timely spatial insights into vegetation and water stress conditions.

Results

This study assessed vegetation health and drought conditions across Taiwan using NDVI and VCI indices derived from Sentinel-2, Landsat 8, and MODIS satellite datasets for the periods 2017–2023, 2013–2023, and 2001–2023, respectively.

The NDVI values obtained from Sentinel-2 imagery showed clear seasonal dynamics, with higher values during the summer months, consistent with Taiwan's subtropical and tropical climate that favors active vegetation growth. Conversely, lower NDVI values during winter months reflect reduced vegetation activity due to seasonal dormancy. The multi-year NDVI average indicated relatively stable vegetation cover with moderate fluctuations attributed to interannual climatic variability.

VCI calculations, based on the pixel-wise NDVI minimum and maximum values across the study period, enabled effective normalization of vegetation health across years and landscapes. The spatial distribution of VCI classes revealed distinct zones of extreme, severe, moderate, and mild drought. The areas experiencing extreme drought are mainly located in northern and western Taiwan. These regions are crucial for agriculture and water resource planning.

The figure presents a comparison of NDVI and VCI values obtained from three satellite datasets Sentinel-2, Landsat 8, and MODIS over various time periods. In panels (a–b), which are based on Sentinel-2 data from 2017 to 2023, we see that NDVI values have remained fairly stable, suggesting that the overall vegetation cover has not changed much. On the other hand, VCI shows more pronounced fluctuations from year to year, which points to its greater sensitivity to short-term climate changes and environmental stressors. This really underscores how valuable the index is for spotting seasonal and interannual drought conditions.

The panels (c–d) that analyze the period from 2013 to 2023 using Landsat 8 data indicate a slight upward trend in NDVI, which suggests that vegetation density might be on the rise. This increase could be tied to changes in land use or more favorable climate conditions. However, the VCI values show significant fluctuations, with notable drops in 2015 and 2019 years that experienced severe droughts and heightened ecosystem vulnerability.

Panels (e–f), derived from MODIS records between 2001 and 2023, provide a longer-term perspective. NDVI reveals a gradual positive trend, suggesting improvements in vegetation health over two decades. However, VCI data indicate recurring episodes of drought stress, particularly in the western lowlands. These patterns imply that while vegetation cover has generally expanded, the region

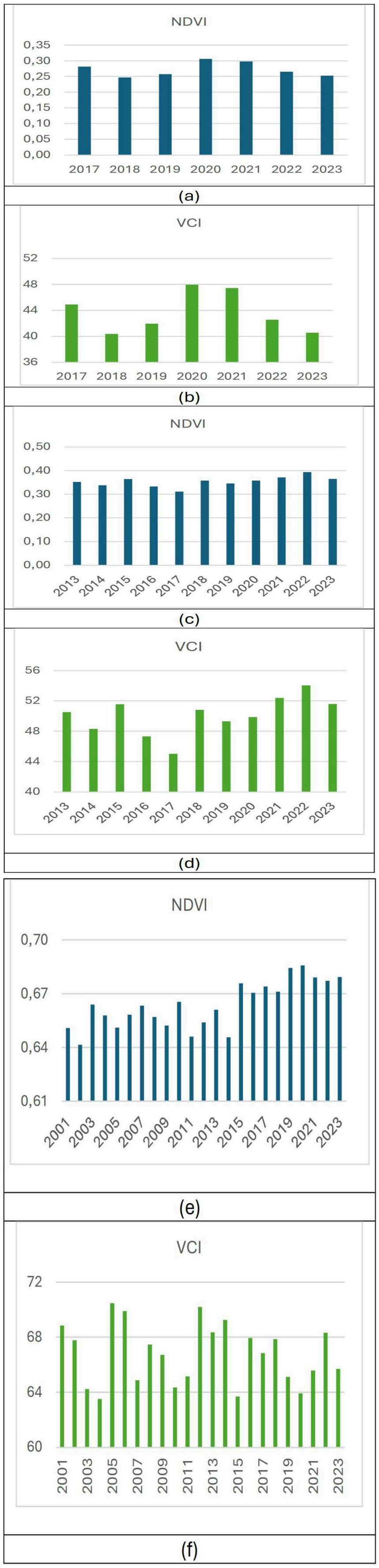

Figure 3. (a–b) Sentinel-2 imagery, (c–d) Landsat 8 imagery, and (e–f) MODIS imagery.

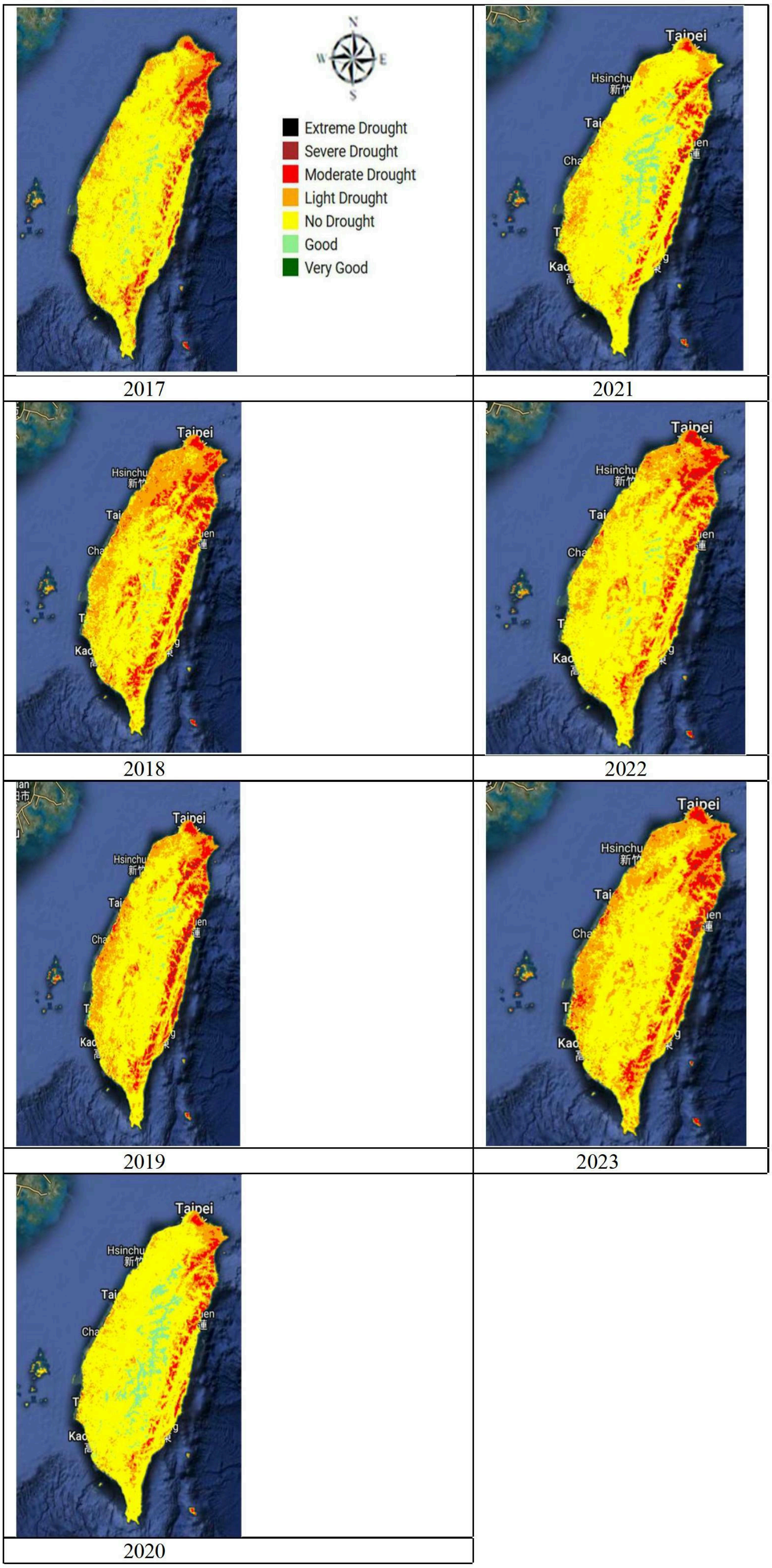

Figure 4. Drought Map from 2017 to 2023 derived from Sentinel 2 satellite data.

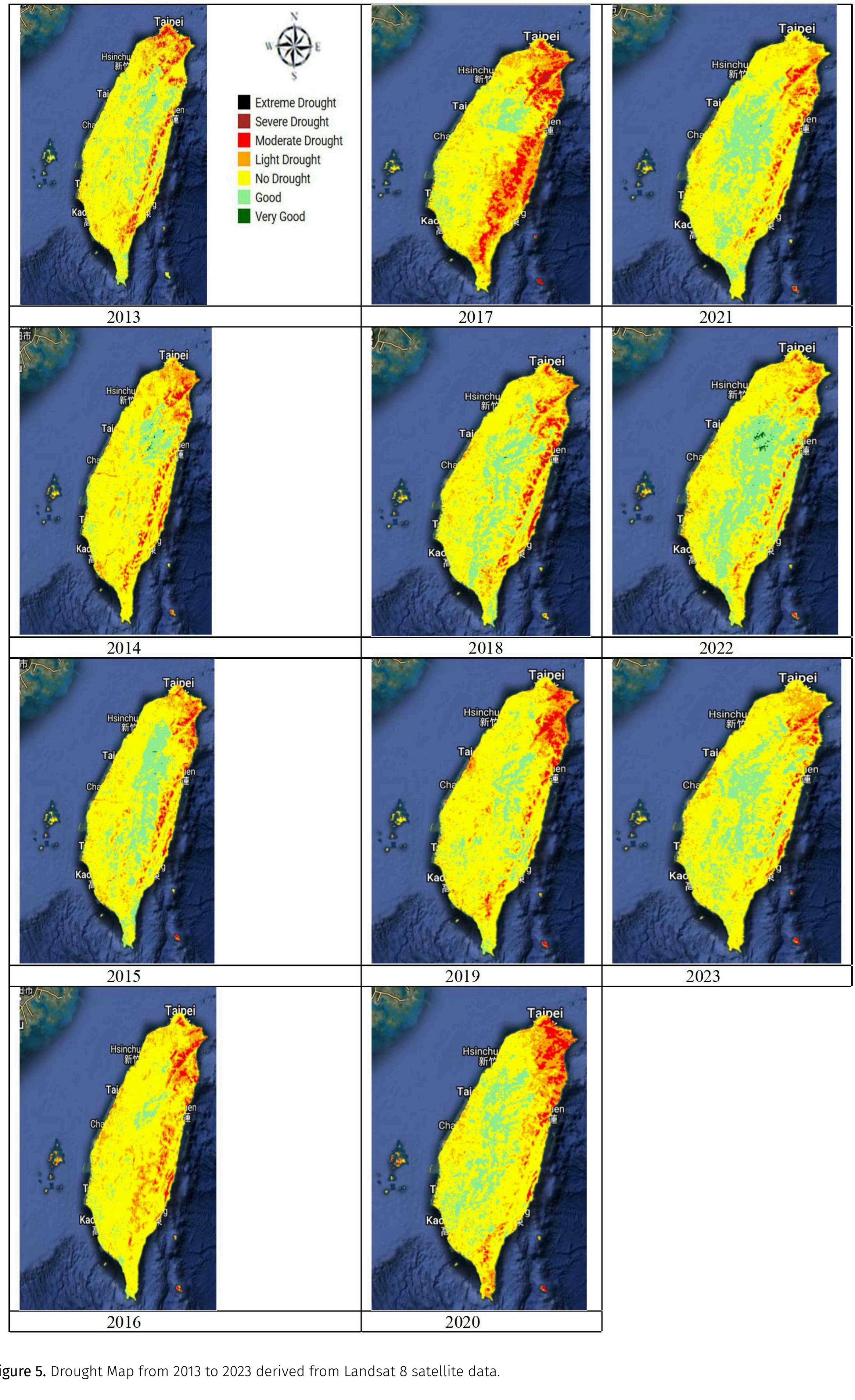

Figure 5. Drought Map from 2013 to 2023 derived from Landsat 8 satellite data.

continues to face periodic droughts, underscoring the importance of sustained monitoring.

Figure 4 presents drought maps from 2017 to 2023 derived from Sentinel-2 satellite data. The Sentinel-2-derived drought maps illustrate annual fluctuations in vegetation stress across Taiwan from 2017 to 2023. In 2017, vegetation appeared generally healthy across the island, although localized drought pockets were evident in both coastal and inland areas. The year 2018 was marked by notably high VCI values, indicating optimal vegetation conditions and minimal drought stress. However, in 2019, a substantial decline in VCI was observed, especially in central and northwestern Taiwan, where severe drought patches emerged. Between 2020 and 2023, while overall drought severity was moderate, spatial patterns shifted, with the Chungyang Mountains and northern Taiwan consistently exhibiting signs of persistent water stress. These dynamic spatial-temporal patterns emphasize the variability of drought conditions and the need for regular monitoring.

Figure 5 illustrates the drought maps from 2013 to 2023, derived from Landsat 8 satellite data. Landsat 8-based drought maps over a decade (2013–2023) reinforce the spatial patterns observed with Sentinel-2, particularly highlighting 2017 as a year of peak vegetation health. Conversely, the years 2015 and 2019 were characterized by significant vegetation stress, aligning with global El Niño events and regional dry spells. The recurrence of drought conditions in northern and central plains—areas of intensive agriculture and urban development—suggests structural vulnerabilities exacerbated by land use pressure. These patterns reflect

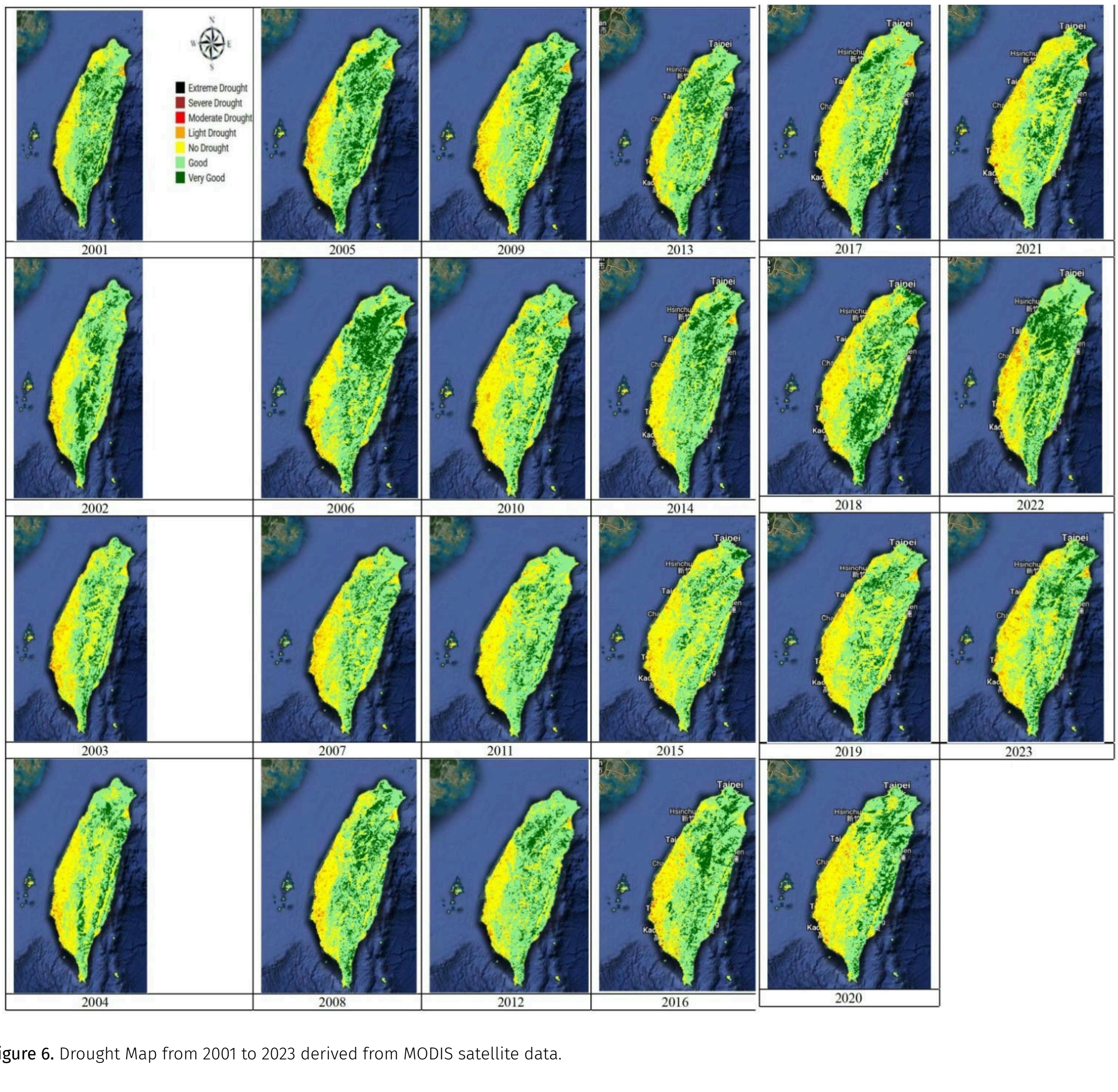

Figure 6. Drought Map from 2001 to 2023 derived from MODIS satellite data.

not only climatic influences but also anthropogenic factors, highlighting priority areas for adaptive land and water resource management.

Figure 6 depicts drought maps from 2001 to 2023, derived from MODIS satellite data. The analysis of the Vegetation Condition Index (VCI) values reveals a consistent pattern of drought conditions over the years. Throughout this period, the data indicates that drought conditions have been notably severe in the western regions. Although there is a broad range of VCI values across the years, the western areas consistently exhibit higher maximum VCI values, reflecting a more pronounced impact of drought in these regions compared to others.

Long-term MODIS observations from 2001 to 2023 reveal persistent drought stress in western Taiwan, particularly in coastal zones and major river valleys. These regions consistently recorded lower VCI values than the rest of the island. Notably, the years 2002, 2007, 2011, and 2019 correspond with extremely low VCI values, aligning with severe droughts documented in Taiwan's meteorological records. Although NDVI shows a gradual upward trend, reflecting improvements in vegetation cover, VCI highlights the recurrence of drought stress—likely linked to uneven rainfall, rising temperatures, and intensified land use. Together, these results emphasize the chronic nature of drought in western Taiwan and the pressing need for long-term adaptation measures.

The combined use of Sentinel-2, Landsat 8, and MODIS datasets provides a multi-scale and multi-temporal view of drought and vegetation dynamics. High-resolution Sentinel-2 data allow for localized assessments, Landsat 8 offers medium-scale continuity, and MODIS supplies a long-term perspective. This integration strengthens the ability to identify both short-term fluctuations and broader drought trends.

Time series of NDVI and VCI proved effective for assessing ecosystem health under changing climate conditions. The results highlight:

- pronounced seasonal and interannual variability in vegetation health, with greater impacts in drought-prone areas,
- persistent drought stress in northern and western Taiwan, suggesting the need for region-specific management strategies, and
- the value of remote sensing tools for ecosystem monitoring where field-based data are limited.

Overall, these findings contribute to improved drought preparedness, agricultural planning, and ecosystem conservation, offering critical insights for climate adaptation in Taiwan.

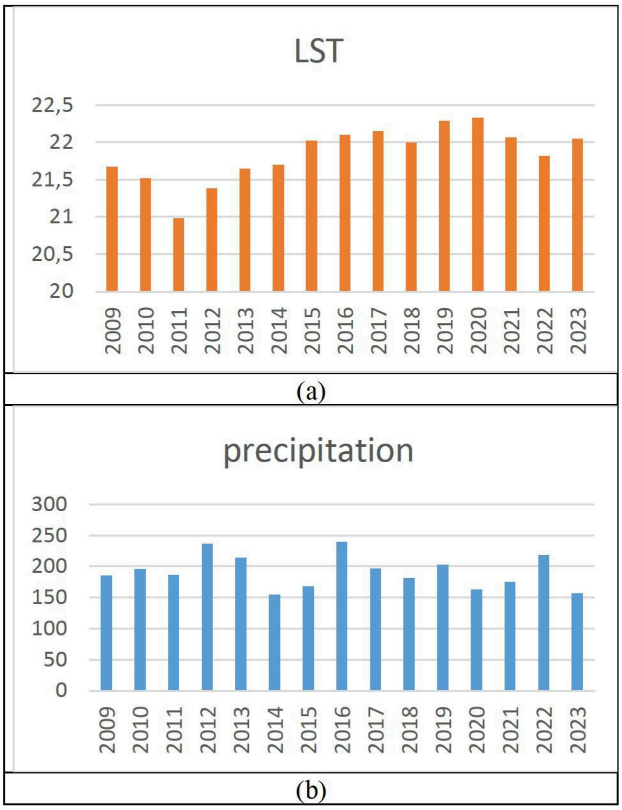

Figure 7. (a) LST, (b)precipitation data.

Figure 7 illustrates the temporal variation in annual average Land Surface Temperature (LST) and total precipitation across Taiwan between 2009 and 2023. The data were obtained from the Central Weather Administration (CWA) of Taiwan, which provides official meteorological records. Monthly average values from ground-based observations were used to compute annual means. As the CWA's consistent and reliable digital records begin in 2009, only post-2009 data were included in the analysis.

LST values over the 15-year period ranged approximately from 21.0 °C to 22.3 °C. A noticeable minimum was recorded in 2011 (around 20.98 °C), followed by a gradual increase, reaching a peak in 2020 (22.33 °C). This indicates a general warming trend in Taiwan's surface temperature over the observed period.

In contrast, precipitation values displayed significant interannual variability. Notably, 2012 and 2016 recorded the highest annual totals (236.78 mm and 239.79 mm, respectively), while 2014 (154.29 mm) and 2023 (155.83 mm) experienced notably lower totals. These fluctuations are likely linked to Taiwan's complex subtropical climate, orographic influences, and seasonal monsoon patterns.

Overall, the trends depicted in Figure 7 highlight the dynamic nature of Taiwan's climate and reinforce the importance of incorporating long-term LST and precipitation data when assessing vegetation indices such as NDVI and VCI. These climatic variables form a crucial foundation for understanding ecosystem responses and conducting further regression-based modelling analyses.

Table 1. Regression models.

Satellite	Regression	R^2	RMSE	MAE
Sentinel2	LST Precipitation → NDVI	0.197	0,019	0,018
	LST, Precipitation → VCI	0.194	2.605	2.421
Landsat8	LST, Precipitation → NDVI	0.058	0.020	0.013
	LST, Precipitation → VCI	0.099	2.273	1.756
Modis	LST, Precipitation → NDVI	0.725	0.006	0.005
	LST, Precipitation → VCI	0.279	1.643	1.295

Table1. 1. Data from various satellite sensors, including Sentinel-2, Landsat 8, and MODIS, was used to perform several linear regression analyses in this study. To evaluate model performances, the same metrics were used to include the temporal coverage of each satellite dataset, such as the coefficient of determination (R2), root mean square error (RMSE), and mean absolute error(MAE). The Linear Regression model from the scikit-learn library in Python was utilized for all regression analyses.

The results obtained for the Taiwan region indicate that MODIS data exhibited significantly higher explanatory power in modelling both NDVI and VCI compared to the other satellite systems. Specifically, the regression model for NDVI based on MODIS data achieved a determination coefficient of R^2 = 0.7253, suggesting that LST and precipitation variables, when derived from MODIS, strongly explain vegetation dynamics. The model's low RMSE (0.0068) and MAE (0.0055) values further confirm its high predictive accuracy.

The regression model for VCI, while offering a moderate explanatory capacity (R^2 = 0.2793), still outperformed the models based on Sentinel-2 and Landsat 8. Due to the limited temporal coverage of Sentinel-2, relatively lower accuracies were observed in the NDVI (R^2 = 0.1975) and VCI (R^2 = 0.1943) models. Similarly, Landsat 8-based models demonstrated limited explanatory power, with R^2 values of 0.0582 for NDVI and 0.0990 for VCI, respectively.

These findings emphasize that MODIS, with its long temporal record and high temporal resolution, serves as a more effective tool for modelling the relationships between vegetation indices and climatic variables in regions such as Taiwan, which exhibit complex and heterogeneous topo-climatic conditions.

Discussion

Through the use of Sentinel-2, Landsat 8, and MODIS, as well as other satellite sources, this study investigated Taiwan' climatic conditions through drought patterns and vegetation health. According to the findings, NDVI obtained from Sentinel-2 accurately captures both seasonal and year-to-year changes in plant and animal cover. Taiwan's subtropical and tropical climate supported the anticipated peak of NDVI values during summer, which in turn indicated active plant growth, while lower values in winter resulted in reduced growth and seasonal stress. Taiwan's vegetation is highly susceptible to seasonal climatic changes, as indicated by its regular patterns.

The Vegetation Condition Index (VCI) was developed from long-term NDVI records, and provided a standardized view of vegetation stress and drought severity. VCI mapping demonstrated that northern and western Taiwan are more prone to severe droughts than other areas, which is particularly important due to their agricultural and water resources. This spatial variability is useful for assessing the risk of drought in the region and early warning systems.

Analysis of interannual VCI variations showed that drought impacts are not uniform across the island. For instance, 2019 and 2020 experienced widespread severe drought, particularly affecting lowland agricultural areas. Such variability reflects the influence of regional climate anomalies, including typhoon occurrences, irregular rainfall patterns, and broader climate oscillations. Notably, while NDVI values remained relatively stable over time, VCI exhibited much higher fluctuations, highlighting its sensitivity to short-term stressors such as rainfall deficits and temperature extremes.

Combining Sentinel-2's high spatial resolution, Landsat 8's historical coverage, and MODIS's frequent, long-term observations proved effective for multi-scale monitoring. This integration allowed both short-term anomalies and long-term ecosystem responses to be captured more comprehensively. Supporting this, Figure 7 illustrates the connections between vegetation dynamics, precipitation patterns, and land surface temperature, while regression analyses in Figure 8 show that MODIS-based data provided stronger explanatory power for NDVI and VCI variations, emphasizing the value of long-term, high-frequency datasets in ecological studies.

Despite these insights, certain limitations exist. Sensor differences, cloud cover, and atmospheric effects may introduce inconsistencies in the datasets. Additionally, the lack of extensive ground-based validation limited the full confirmation of satellite-derived results. Future studies could benefit from combining field observations, meteorological data, and advanced modeling techniques, such as machine learning, to further enhance the accuracy of drought and vegetation assessments.

Overall, this study demonstrates that satellite remote sensing provides a reliable and insightful approach for monitoring vegetation health and drought dynamics in Taiwan. The findings improve understanding of ecosystem responses to climate variability and offer a solid methodological foundation for enhancing drought preparedness and regional adaptation planning.

Conclusion

The utilization of Sentinel-2, Landsat 8, and MODIS in conjunction with cloud-based platforms like Google Earth Engine (GEE) to monitor drought and vegetation health in Taiwan is emphasized in this study. These results are preliminary. By utilizing both NDVI and VCI, it became possible to assess spatial and temporal drought patterns with precision, thereby pinpointing the areas of greatest vulnerability in ecosystems and regions of interest.

The study focuses on Taiwan's land ecosystems and examines data from 2001 to 2023 to illustrate the impact of drought and climate variability. The results indicate that VCI can be a highly sensitive indicator of vegetation stress, especially when applied in multi-temporal and multi–sensor settings.

The results also highlight the broader importance of integrating diverse data sources and modeling approaches for environmental monitoring and early warning at larger scales. Leveraging satellite observations, ecosystem process understanding, and cloud computing can improve disaster preparedness, guide adaptive land-use decisions, and support sustainable management of natural resources. The regression analyses, especially the strong performance of MODIS datasets (Figure 8), emphasize the value of long-term, high-frequency satellite records in capturing ecological dynamics effectively.

Overall, this study contributes both methodological and practical insights, offering a foundation for science-based policy development in agriculture, urban planning, and environmental conservation under changing climate conditions.

Moreover, the study identifies critical areas for future research, such as:

- Integration of in-situ ground measurements for validation,
- Incorporation of machine learning models for drought prediction,
- Assessment of ecosystem service trade-offs under drought conditions,
- Analysis of land use and urbanization impacts on regional drought risk.

In conclusion, this research contributes to the advancement of integrated ecosystem monitoring methodologies and demonstrates the utility of satellite data in supporting adaptive management and climate resilience. The results offer a valuable reference for Taiwan and other regions with similar climatic vulnerabilities, reinforcing the need for data-driven decision-making in environmental governance.

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