






PRACTICAL CASE

# Spatial-temporal assessment of Uaymil Protected Area conservation status using an ecosystem quality index from 2000-2023

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**Abstract:** Protected areas (PAs) are crucial for conserving species and ecosystems but are still susceptible to deforestation and degradation from human and natural causes. The Uaymil Protected Area in Quintana Roo, Mexico, is a key ecological corridor facing deforestation risks due to its location. Due to this, the objective of this study was to evaluate the conservation status and analyse the spatial-temporal changes of the protected area of flora and fauna from "Uaymil" using the Ecosystem Quality Index (EQI). MODIS (Moderate Resolution Imaging Spectroradiometer) Terra satellite data for Leaf Area Index (LAI), Gross Primary Productivity (GPP), and Fractional Vegetation Cover (FVC) were used to calculate the annual EQI over 23 years. The results showed a strong integration of LAI, GPP, and FVC into the EQI, improving the ability of the model to capture ecosystem quality changes. Significant shifts occurred in 2005, 2011, 2015, and 2023, indicating both degradation and recovery. Lower EQI values were found in mangrove and marsh areas, while forests had higher ecological values. Overall, the Uaymil Protected Area maintains high vegetation cover and ecosystem quality, indicating a strong conservation status.

**Key words:** protected area conservation, ecosystem evaluation, remote sensing, spatial-temporal assessment; conservation status.

## Evaluación espacio temporal del estado de conservación del Área Protegida Uaymil utilizando un índice de calidad del ecosistema 2000-2023

**Resumen:** Las áreas protegidas (AP) son cruciales para la conservación de especies y ecosistemas, pero aún son susceptibles a la deforestación y la degradación por causas humanas y naturales. El Área Protegida Uaymil en Quintana Roo, México, es un corredor ecológico clave que se enfrenta al riesgo de la deforestación debido a su ubicación. En consecuencia, el objetivo de este estudio fue evaluar el estado de conservación y analizar los cambios espacio-temporales del área protegida de flora y fauna en "Uaymil" utilizando el Índice de Calidad del Ecosistema (EQI). Se utilizaron datos satelitales MODIS (*Moderate Resolution Imaging Spectroradiometer*) Terra para obtener el Índice de Área Foliar (LAI), la Productividad Primaria Bruta (GPP) y la Fracción de Cubierta Vegetal

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(FVC) y calcular el EQI anual durante 23 años. Los resultados mostraron una fuerte integración de LAI, GPP y FVC en el EQI, mejorando la capacidad del modelo para capturar los cambios en la calidad del ecosistema. En 2005, 2011, 2015 y 2023 se produjeron cambios significativos, lo que indica tanto degradación como recuperación. Se encontraron valores más bajos de EQI en las áreas de manglares y marismas, mientras que los bosques tuvieron valores ecológicos más altos. En general, el Área Protegida Uaymil mantiene una alta cobertura vegetal y calidad del ecosistema, lo que indica un robusto estado de conservación.

**Palabras clave:** conservación de áreas protegidas, evaluación de ecosistemas, teledetección, evaluación espaciotemporal, estado de conservación.

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## 1. Introducción

Protected areas (PAs) play a crucial role in safeguarding ecological diversity, ecosystem services and promoting sustainable resource management (Holdgate and Phillips, 1999; Gungor, 2007; Corrigan et al., 2018; Campos-Silva and Peres., 2021). However, PAs are susceptible to both anthropogenic and natural alterations that lead to degradation, deforestation, fragmentation and species extinction (Verburg et al., 2006; Ponce-Reyes et al., 2012; Laurance et al., 2012; Gálvez et al., 2013; Reza, 2014; Schulze et al., 2017; De Matos et al., 2019; De Sales et al., 2020; Pedraza et al., 2020; Wade et al., 2020; Devine et al., 2021; Sergio et al., 2021; Mohammadi and Fatemizadeh, 2021; Ebright et al., 2023). From 2001 to 2018, over 25.5 million hectares of forest within PAs have been lost worldwide, whereas only between 20% and 50% of PAs are effectively conserved (Watson et al., 2014; Heino et al., 2015; Wade et al., 2020). To address this, developing comprehensive strategic management and action plans to evaluate ecosystems within PAs is essential. This valuation should assess the conservation status within PAs to determine the condition and the factors that affect or increase the ecosystems' resilience and stability (Maciejewski et al., 2016).

In Europe, the conservation status assessment plays a key role in PAs management and the compilation of Habitat Directive Article 17 objective (European Commission and Institute for Environment and Sustainability [EU-IES], 2013). Ecosystem composition, structure, and function are crucial ecological metrics for assessing the conservation status of ecosystems (Cantarello and Newton, 2008; Maciejewski et al., 2016; Kovac et al., 2020; Bou and Vilar,

2021; Biswas et al., 2022). Conservation status has been widely analysed for assessing habitat protection, conservation effectiveness, and status in all types of ecosystems including fragmented vegetation and vegetation along rural roads (Cysneiros et al., 2015; Santibañez-Andrade et al., 2015; Biswas et al., 2022). While the conservation status assessment provides a valuable framework, it faces several challenges: field assessments are costly, selecting measurable indicators requires ecosystem-specific expertise, defining stability is complex, and comparisons depend on long-term temporal field data and analysis (Alberdi et al., 2019). For this reason, the use of remote sensing and spectral indices constitutes a key methodological approach to evaluate conservation status.

The Ecosystem Quality Index (EQI) is a spectral index developed by the Chinese Ministry of Environment [MEE] (2021) to evaluate the dynamic change pattern, restoration, protection effectiveness, and resilience of ecosystems (Guo et al., 2023). Several studies have utilized this index for various purposes, such as assessing ecosystem damage, degradation, pressure, and ecological zoning (Zheng et al., 2023), and for evaluating the spatial-temporal quality of ecosystems in Hanan province (Ren et al., 2022). Additionally, studies by Wang et al. (2022), Wang et al. (2023), Zhang et al. (2023) and Zhao et al. (2023) have used this index in various contexts to study ecosystems. Hence, EQI is a robust indicator that combines three spectral vegetation indicators to provide a comprehensive view of overall vegetation state, surpassing the limitation of single indicators (Zhao et al., 2023). This underscores its significance as a crucial methodological tool for assessing ecosystem condition across both

spectral and temporal scales, and its application in this study.

Uaymil Flora and Fauna Protected Area is part of the Sian Ka'an Biosphere Complex. This reserve serves as an important ecological corridor with wetland ecosystems registered under Ramsar Convention that additionally encompasses a significant marine and hydrological zone (Secretaría de Medio Ambiente y Recursos Naturales [SEMARNAT], 2016). The main objective of Uaymil PA is conservation, management, and restoration of the biological diversity, landscape, and optimal ecological condition. This is achieved through the establishment of policies and measures to control ecosystem deterioration and improve environmental condition. For instance, some studies have highlighted the vulnerability of the Sian Ka'an-Uaymil complex to deforestation. A report covering 2000-2008 by Velasco-Tapia (2009) indicates a loss of 14412 ha of forest vegetation, mainly due to forest fires, agricultural expansion, and pasture development. This deforestation trend could be linked to the location of Sian Ka'an Biosphere Complex within a high deforestation zone (Bacalar municipality) (Huchin-Ochoa *et al.*, 2022). But in fact, few studies have been conducted on the status of ecosystems within Uaymil. Therefore, this study aimed to evaluate the conservation status and analyze the spatial temporal changes within vegetation type of the PA of flora and fauna "Uaymil" using the EQI.

## 2. Materials and Methods

### 2.1. Study area

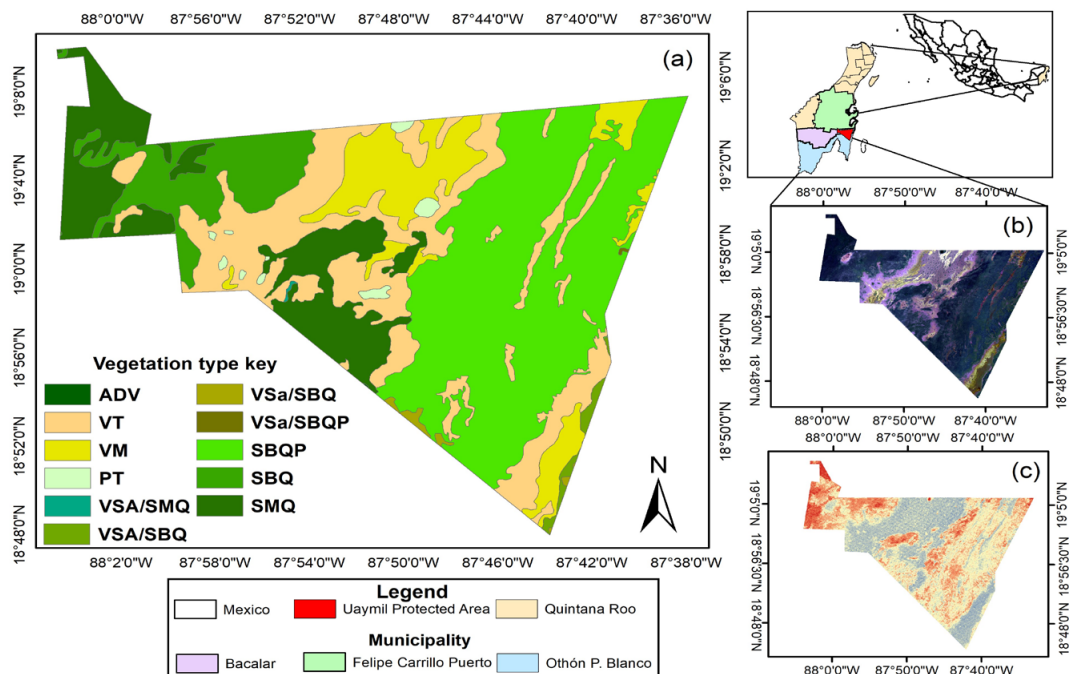
The Uaymil Flora and Fauna Protected Area, established on November 17, 1994, is located in the municipalities of Felipe Carrillo Puerto, Bacalar, and Othón P. Blanco in Quintana Roo, Mexico (18° 59' 13" N, 87° 48' 25" W) (Figure 1). This area covers 89,118 ha and is part of the Sian Ka'an Biosphere Reserve Complex.

Uaymil is comprised of 11 distinct ecosystem types, as identified by the Instituto Nacional de Estadística y Geología [INEGI] (2018) land use and cover map VII series (Figure 1a): this include ADV with 4.13 ha (Areas devoid of vegetation: surface where vegetation was removed by human

activities); PT with 701.7 ha (wetland forests: island of sub-evergreen vegetation within mangrove, *Halophytic* vegetation or swamp area, between 8 and 12 m); SBQ with 8330.9 ha (sub-evergreen low thorn forests: sub-evergreen vegetation between 5 and 11 m, within lowland flood prone areas); SBQP with 35517.5 ha (sub-evergreen low forest between 4 and 14 m, within lowland or plane surface with some degree of flooding); SMQ with 13574.7 ha (sub-evergreen medium forests between 15 and 25 m, hence with a seasonal loss of 20 to 50 % of foliage); VM with 9545.1 ha (mangroves vegetation between 1 to 30 m, located on the margins of lagoons estuaries, mouths of rivers and streams); and VT with 20444.8 ha (marshes: aquatic plant community mostly belonging to *Typhaceae*, *Cyperaceae*, *Poaceae* families within lagoons, freshwater/saltwater lakes with little depth, swampy areas, canals and backwaters of rivers).

Additionally, Uaymil includes secondary vegetation types such as VSA/SBQ with 597.5 ha (secondary tree vegetation of low sub-evergreen thorny forests: sub-evergreen low forest result of the regeneration process due to human activities); VSA/SBQ with 356.2 ha (secondary sub-evergreen low thorn forests with spiny shrubby vegetation: sub-evergreen low forest dominated by thorny shrub species result of the regeneration process due to human activities); VSA/SBQP with 25.6 ha (secondary sub-evergreen low forests with shrubby vegetation: sub-evergreen low forest dominated by shrub species result of the regeneration process due to human activities); and VSA/SMQ with 39.0 ha (secondary sub-evergreen low forests with arboreal vegetation: sub-evergreen medium forest result of the regeneration process due to human activities).

The elevation in Uaymil ranges from -19 meters in mangrove and marsh ecosystems to 20 meters in areas with sub-evergreen lowland thorn and medium forests, according to ALOS PALSAR DEM data (Figure 1b). These ecosystems are crucial for conservation, forming a mosaic that protects the upper basin of Espiritu Santo Bay. Additionally, Uaymil serves as a vital habitat for species such as jaguars, ocelots, pumas, white-tailed deers, and anteaters (Secretariat of Environment and Natural Resources [SEMARNAT], 2016).



**Figure 1.** Overview of the study area. (a) Location of the study area and vegetation type. (b) ALS0 PALSAR DEM. (c) 2023 Landsat 8 image R,G,B combination (B6-B5-B4).

## 2.2. Satellite and data processing

This study uses three different MODIS (Moderate Resolution Imaging Spectroradiometer) satellite products (Wang *et al.*, 2022): MOD13Q1 that contains the Normalized Difference Vegetation Index (NDVI), with a 16-day 250 m spatial resolution (Didan and Barreto-Muñoz, 2019); MOD15A2H that contains values of the Leaf Area Index (LAI), with an 8-day 500 m spatial resolution (Myneni *et al.*, 2015); MOD17A2 that contains data on Gross Primary Productivity (GPP), with an 8-day 500 m spatial resolution (Running and Zhao, 2019).

The MODIS products were acquired from the NASA LAADS DAAC (<http://ladsweb.modaps.eosdis.nasa.gov/search/order>) for the years 2000, 2005, 2011, 2015, and 2023. A comprehensive examination of satellite images was conducted to ensure that the best images were used for an annual analysis. Images with distorted pixels within the study area were discarded, resulting in the retention of 19 MODIS images of each product, totalling 57 MODIS images, with path and row 09/07. Each year

included approximately four images, except for 2023 where only three images were obtained (Table 1).

MODIS Terra data utilized in this study was first converted from MODIS HDF data to GeoTIFF format. Subsequently, the satellite image product was reprojected to WGS 1984 UTM Zone 16N. Due to differences in resolution from the MODIS products (LAI and GPP: 500 m; NDVI: 250 m), resampling (nearest-neighbour method) was done to 250 m resolution for a better integration of images, to maintain consistency and for a finer resolution before conducting the EQI composite analysis (Santhosh-Baboo and Renuka-Devi, 2010; Bartmiński and Siłuch, 2020). The next step involved applying multiple scale factor for radiometric calibration (scale factor LAI: 0.1; NDVI: 0.0001; GPP: 0.0001) (Didan and Barreto-Muñoz, 2019; Running and Zhao, 2019). After image processing, the annual mean of NDVI, LAI, and GPP were obtained. Lastly, the study area was extracted using the masking tool of ArcMap 10.8.

**Table 1.** Satellite image acquisition data.

Sensor	Product	Satellite resolution	Path/Row	Acquisition date
Terra-MODIS (Moderate resolution imaging spectroradiometer)	MOD13Q1 (NDVI data)	250 m	09/07	21/03/2000
				25/04/2000
				02/12/2000
				18/12/2000
				17/01/2005
Terra-MODIS (Moderate resolution imaging spectroradiometer)	MOD15A2H (LAI data)	500 m		02/02/2005
				14/09/2005
				17/11/2005
				18/02/2011
				07/04/2011
				17/11/2011
Terra-MODIS (Moderate resolution imaging spectroradiometer)	MOD17A2HGF (GPP data)	500 m		07/12/2011
				17/01/2015
				02/02/2015
				23/04/2015
				30/08/2015
				25/05/2023
				16/10/2023
17/11/2023				

### 2.3. Ecosystem Quality index

The Ecological Quality Index (EQI) developed by the Chinese Ministry of Ecology and Environment (MEE) utilizes three primary ecosystem spectral indices: Leaf Area Index (LAI), Gross Primary Production (GPP), and Fractional Vegetation Cover (FVC) (Ren *et al.*, 2022; Wang *et al.*, 2022). LAI and GPP values are obtained from MODIS products, while FVC is calculated using MOD13Q1 NDVI data, with the dense vegetation mosaic pixel model by Gutman and Ignatov (1998) (1).

$$FVC = \frac{NDVI - NDVI_{soil}}{NDVI_{veg} - NDVI_{soil}} \quad (1)$$

Where NDVI is the Normalized Vegetation Index;  $NDVI_{soil}$  is the NDVI value of pure bare soil;  $NDVI_{veg}$  is the maximum NDVI value.

For calculating the annual EQI, the initial step involved to determine the Relative Vegetation Index (RVI) of ecological indicators by ecosystem type, using the Instituto Nacional de Estadística y Geología [INEGI] (2018) land cover maps, and to identify the vegetation types within the PA. LAI, GPP, and FVC values were extracted for each vegetation type using masking techniques, and RVI was calculated using the Chinese Ministry of Environment [MEE] (2021) formula (2):

$$RVI_{i,j,k} = F_{i,j,k} / F_{max_{i,j,k}} \quad (2)$$

Where  $RVI_{i,j,k}$  is the relative density of ecological parameters for vegetation type  $k$  in Zone  $j$  in year  $i$ ;  $F_{i,j,k}$  is the value of the ecological parameter;  $F_{max_{i,j,k}}$  is the maximum value of the ecological parameter.

These RVI values were then merged, and all indices were normalized using Chinese Ministry of Environment [MEE] (2021) formula (3):

$$X = \frac{x - \min(x)}{\max(x) - \min(x)} \quad (3)$$

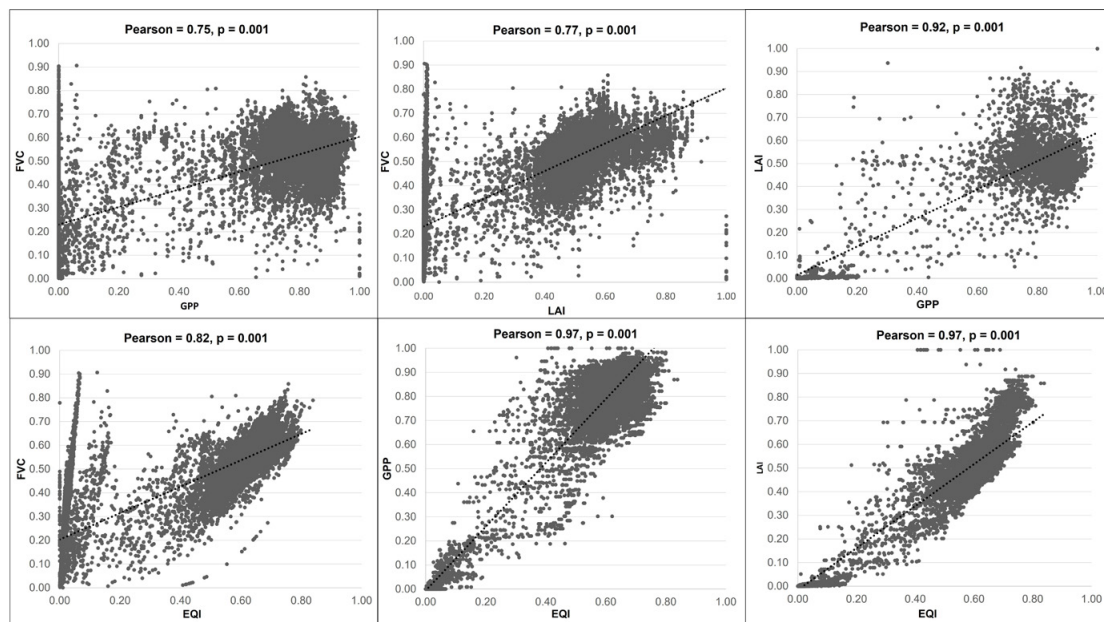
Where  $X$  is the normalized index;  $x$  is the original index;  $\min/\max$  are the minimum and maximum values.

Finally, the EQI was calculated for the analysed years using the Chinese Ministry of Environment [MEE] (2021) formula (4):

$$EQI = (LAI + FVC + GPP) / 3 \quad (4)$$

### 2.4. Ecosystem quality grading

To assess temporal changes in the quality of Uaymil ecosystems, EQI values were categorized



**Figure 2.** Pearsons Correlation of ecological indices and Ecological Quality Index in Uaymil protected area.

into five classes: very low, low, moderate, high, and very high (Chinese Ministry of Environment [MEE] (2021). A very high EQI indicates natural vegetation in a favourable condition, while a very low EQI suggests an unfavourable condition. The EQI for each of the five years was classified using the mean natural break method, a common GIS technique that identifies natural groupings within data and provides a suitable representation of real-world conditions (Brewer and Pickle, 2002; Chen *et al.*, 2013). The resulting EQI categories were very low (0-0.26), low (0.26-0.49), moderate (0.49-0.75), high (0.75-0.89), and very high (0.89-1.0).

## 2.5. Statistical analysis

Before calculating the annual EQI, the ecological indicators (LAI, GPP, and FVC) were normalized (Formula 3) to ensure they were on a comparable scale, allowing for equal contribution to the EQI calculation (MEE, 2021). Although all indicators equally influence the EQI, their complex interrelationships may affect EQI changes differently. To explore these dynamics, we performed a Pearson correlation analysis, among indicators and EQI. Additionally, to evaluate how each indicator integrates with the EQI, with

the EQI as the dependent variable, we conducted multiple and stepwise linear regression analyses. (Zhang *et al.*, 2022; Zhao *et al.*, 2023).

## 3. Results and Discussion

### 3.1. Correlation and regression analysis

The spectral ecological indices (LAI, GPP, and FVC) demonstrate a strong positive correlation with EQI, with Pearson correlation coefficients ranging from 0.75 to 0.97 and a significance level of  $p = 0.001$  (Figure 2). Furthermore, the combination of these spectral ecological indicators significantly enhances the explanatory power of EQI (GPP:  $R^2 = 0.95$ , GPP + LAI:  $R^2 = 0.98$ , GPP + LAI + FVC:  $R^2 = 0.99$ ). This relationship has also been reported by Zhang *et al.* (2022) in mountainous areas of China, where LAI, GPP, and FVC showed strong positive correlations. Similarly, Wang *et al.* (2023) reported a positive correlation between NDVI and EQI, with higher EQI located within dense vegetation. This relationship illustrates a coupled response and recurring pattern in the ecosystem's dynamics, where enhancements or declines in one indicator are systematically reflected by changes in the others.

**Table 2.** Stepwise multiple linear regression analysis of ecological indices in Uaymil protected area.

Stepwise Regression	Ecological Indices	B	Std. Coeff.	Std. Error	Adj. R <sup>2</sup>
1	GPP	0.717	0.976	0.00127	0.95
2	GPP	0.388	0.528	0.00166	0.98
	LAI	0.532	0.486	0.00247	
3	GPP	0.365	0.497	0.00118	0.99
	LAI	0.457	0.418	0.00184	
	FVC	0.186	0.126	0.00146	

*P*-value < 0.001.

### 3.2. Spatial distribution and temporal patterns of ecological indicators

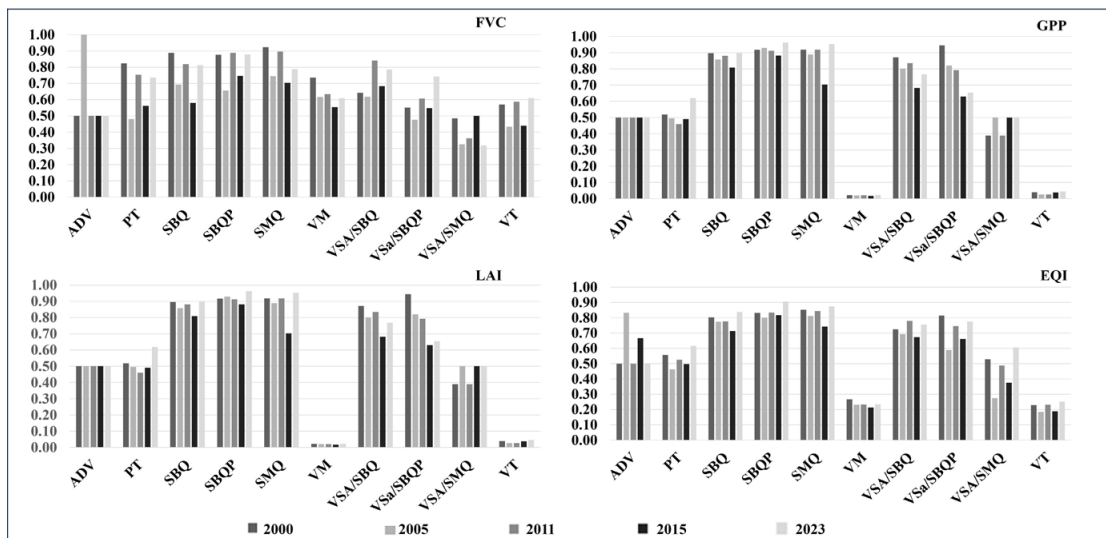
The temporal patterns of ecological indicators reveal clear fluctuations over the study period, which are reflected in their spatial distributions within the Uaymil PA (Table 3, Figures 3 and 4). There were notable changes in mean FVC over time. From 2000 to 2005, the FVC mean decreased by 0.18, indicating a reduction in vegetation coverage. This decline was followed by an increase of 0.17 from 2005 to 2011. A subsequent decrease of 0.15 was observed from 2011 to 2015, with a recovery of 0.13 from 2015 to 2023. These fluctuations are mirrored in the spatial distribution

maps (Figures 3 and 4), where high FVC values were predominantly located in forest ecosystems. However, between 2005 and 2015, a shift towards lower and moderate FVC categories, particularly in marsh and mangrove areas.

The GPP mean exhibited minimal fluctuations compared to FVC. There was a slight decline of 0.01 from 2000 to 2005, stability at 0.62 from 2005 to 2011, a notable decrease of 0.05 from 2011 to 2015, and an increase of 0.08 from 2015 to 2023. This trend was reflected in the spatial distribution, with marsh and mangrove ecosystems showing consistently low GPP, while forest ecosystems exhibited higher GPP values, except for a decrease in very high GPP categories

**Table 3.** Temporal variation of ecological indicators in the Uaymil protected area.

Ecological Indices	Year	Mean	Standard deviation	95% Confidence interval		Interquartile range
				Lower	Upper	
FVC	2000	0.80	0.20	0.79	0.80	0.14
	2005	0.62	0.16	0.61	0.62	0.16
	2011	0.79	0.19	0.78	0.79	0.20
	2015	0.64	0.18	0.63	0.63	0.26
	2023	0.77	0.17	0.76	0.77	0.22
GPP	2000	0.63	0.44	0.62	0.63	0.96
	2005	0.62	0.44	0.61	0.62	0.95
	2011	0.62	0.44	0.61	0.62	0.96
	2015	0.57	0.40	0.56	0.57	0.89
	2023	0.65	0.45	0.64	0.66	0.96
LAI	2000	0.49	0.32	0.48	0.49	0.62
	2005	0.57	0.37	0.56	0.57	0.71
	2011	0.50	0.32	0.40	0.50	0.61
	2015	0.58	0.37	0.57	0.58	0.72
	2023	0.62	0.39	0.61	0.62	0.74
EQI	2000	0.64	0.30	0.63	0.64	0.56
	2005	0.60	0.30	0.59	0.60	0.59
	2011	0.63	0.30	0.63	0.63	0.58
	2015	0.59	0.30	0.58	0.59	0.59
	2023	0.68	0.32	0.67	0.68	0.63



**Figure 3.** Distribution of mean values of ecological indicators and EQI From 2000-2023 per vegetation type.

in 2015, which dropped to high and low ranges in medium to lowland sub-evergreen forests.

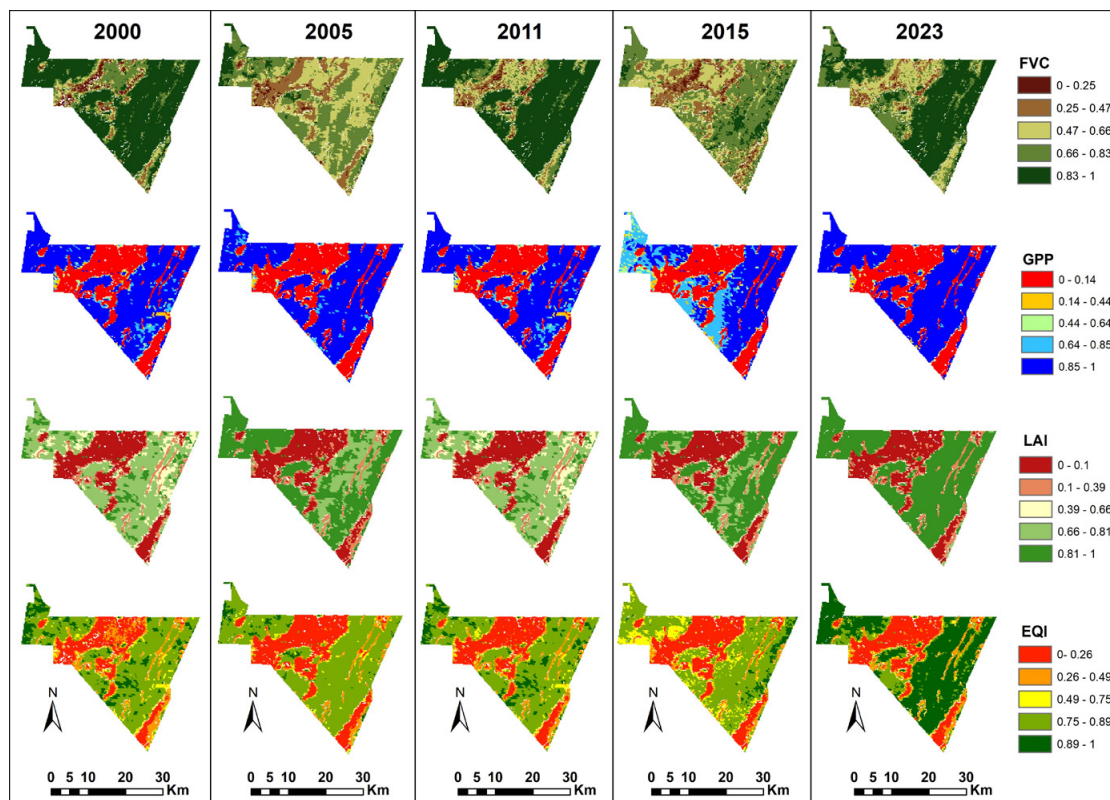
LAI demonstrated a significant increase from 0.49 in 2000 to 0.62 in 2023, with periodic increases and decreases. LAI showed consistent high values in forest ecosystems, while marsh and mangrove areas retained lower LAI categories. The spatial distribution maps revealed an increase in high LAI coverage from 2005 to 2023, indicating a broader expansion of foliage in forested regions. EQI showed reductions in 2005 and 2015, with a mean change rate of 0.04, and an improvement from 2011 to 2023 with an increase of 0.06. EQI increased from 0.64 in 2000 to 0.68 in 2023. Spatially, the distribution of EQI categories highlighted low EQI coverage in mangrove, marsh, devoid of vegetation, wetland forests, and secondary sub-evergreen lowland forests. In contrast, other forest ecosystems showed an increase in high to very high EQI categories, with a notable rise in very high EQI by 2023.

Moreover, a clear pattern was observed where higher EQI categories corresponded to greater vegetation cover, leaf cover, and GPP, while mangrove and marsh ecosystems were often associated with low EQI and ecological indicator categories. In contrast, forest ecosystems typically demonstrated high EQI and ecological indicator values. These findings are consistent with research

conducted by Wei *et al.* (2023), which noted that regions such as Australia, Africa, and Asia generally exhibit low EQI due to low vegetation coverage and productivity, particularly in wetlands, deserts, and shrublands. The consistent observation of low EQI and ecological indicator categories in mangrove ecosystems across different studies suggests that low EQI does not necessarily indicate poor conservation. Mangrove ecosystems frequently exhibit low canopy density, vegetation coverage, and water presence, which can lead to variability in the results of spectral indices and potentially result in misinterpretations (Tran *et al.*, 2022). According to Moore *et al.* (2015), these ecosystems also tend to exhibit low productivity due to above mentioned factors. However, despite these factors, mangrove ecosystems can still be ecologically valuable and play crucial roles in coastal ecosystems.

### 3.3. Uaymil protected area ecosystem quality temporal change

Between 2000 and 2005, the low and high EQI categories dominated the study area, accounting for almost 70-80% of the total surface area. In 2000, the high EQI category, encompassing both high and very high EQI categories, covered 61% (53 011.62 ha of 89,118 ha) of the Uaymil Pa surface area. However, in 2005 there was an increase from 7% to 8% (6425.0 to 7118.6 ha) in surface



**Figure 4.** Spatial distribution of the normalized values in the ecological indicators.

covered with very low and high EQI category, while for moderate, low and very high EQI categories decreased, respectively. By 2011, there was a slight increase in surface covered by EQI categories: 2525.29 hectares in low; 460.8 hectares in moderate, and 2354.2 hectares in very high. In 2015, the area in Uaymil classified under very low and moderate EQI categories increased from 3% to 12% (3004 to 6761.6 ha). Conversely, the surface area of low, high, and very high EQI categories decreased by 3%, 2%, and 5%, respectively. In 2023, there was a significant cover of surface in very high EQI category with approximately 52%

(45450.1 to 89118 ha) of the PA. Overall, during the entire study period, low EQI categories covered 35% (31191.3 ha) of the PA, while optimal EQI categories (high and very high) had the greatest coverage, accounting for 63% (596144.34 ha) of the PA (Table 4).

Most ecosystems in the Uaymil PA show high ecosystem quality index. However, 35% of ecosystems within the PA showed low EQI. Throughout the study period, mangrove and marsh ecosystems consistently fell within the very low to low EQI category, covering about 76.2% of the area classified as low EQI. This equates

**Table 4.** Surface of the EQI categories over 2000 to 2023 in Uaymil protected area.

EQI categories	2000		2005		2011		2015		2023	
	Surface (ha)	%	Surface (ha)	%	Surface (ha)	%	Surface (ha)	%	Surface (ha)	%
Very low	16 641.5	19	23 760.1	27	20 549.2	24	23 553.8	27	20 155.9	23
Low	12 631.4	15	7 070.1	8	9 595.4	11	6 993.6	8	9 523.1	11
Moderate	3 923.8	5	2 908.6	4	3 369.5	4	10 131.1	12	1 863.2	2
High	44 146.3	51	50 571.3	58	45 131.5	52	42 890.0	50	10 604.5	12
Very high	8 865.3	10	2 362.2	3	7 953.4	9	3 075.9	3	44 484.3	52

to 23 777.1 ha out of a total of 31 191.3 ha. The forest vegetation exhibited a substantial coverage of optimal EQI, with most of the forest surface (63%) classified as having excellent ecosystem quality. In contrast, the low EQI categories had a minimal coverage, accounting for 7 414.1 ha, which represents 23.7% of the total area reported as having low EQI (Figure 5). Wetland forests are patches of vegetation within wetland ecosystems; these ecosystems showed 50% of poor coverage and 50% of excellent quality ecosystem index. On the other hand, areas devoid of vegetation, as well as secondary subevergreen low forests characterized by spiny shrubby vegetation, secondary subevergreen low arboreal vegetation, and subevergreen low thorn forests, consistently showed a higher coverage in the low and very low EQI categories throughout the year. Despite some areas showing high EQI, approximately 7%

of the coverage was of poor quality (Figure 5), indicating potential impacts and suggesting the need for a restoration plan.

Notably, the coverage of very low EQI categories increased during certain years, particularly in 2005, 2011, and 2015. While this study did not focus on analyzing the factors contributing to these changes, several reports and studies have identified potential causes. For example, the Comisión Nacional para el Conocimiento y Uso de la Biodiversidad [CONABIO] (2024) from the Forest Fire Early Warning System (2000-2021) recorded fires in 2003, 2007, 2011, 2013, and 2016 within Uaymil. Velasco-Tapia (2009) identified fires as a major cause of deforestation and forest transformation within the Sian Ka'an-Uaymil Biosphere Reserve. Hurricanes have also been significant drivers of change. For instance, Whigham *et al.* (2003) and Pat-Aké *et al.* (2018)

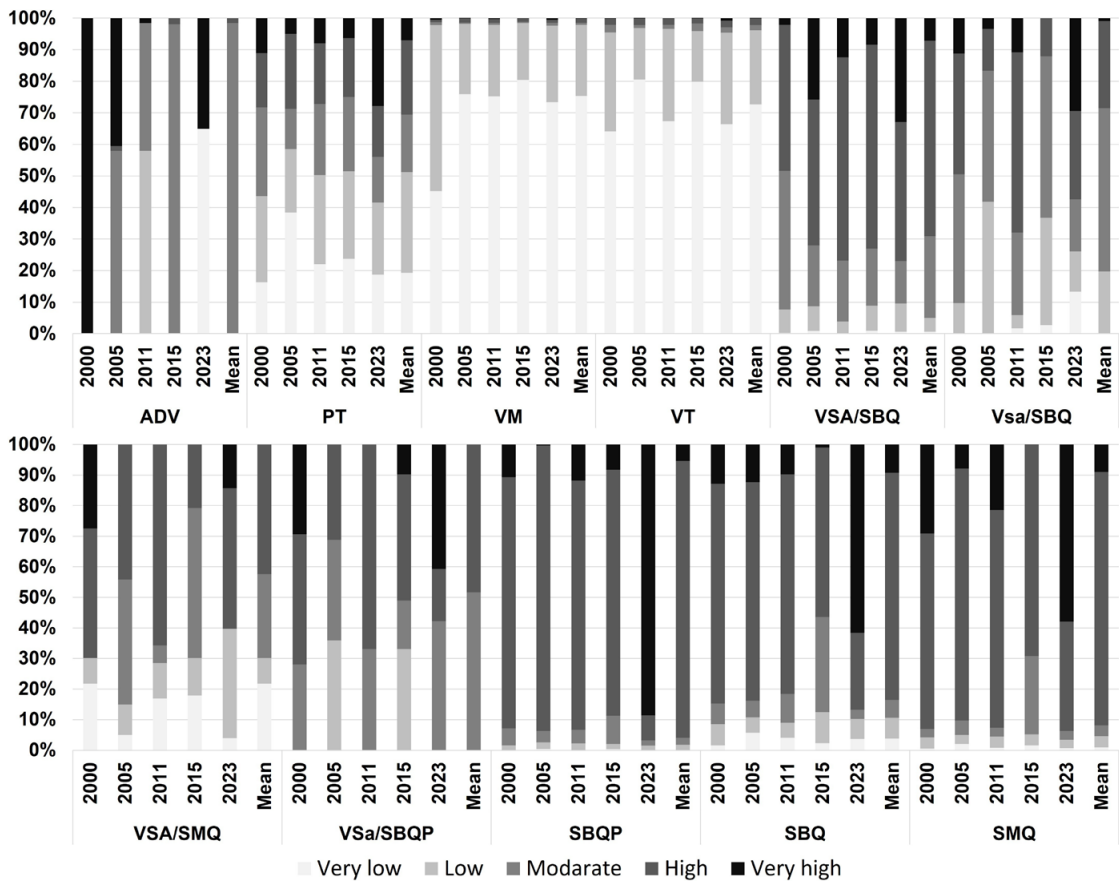


Figure 5. Area proportion of the EQI over 2000 to 2023 by vegetation type.

reported that hurricanes caused significant reductions in canopy cover and basal area, increased tree mortality and tree damage, with effects lasting up to five years. Between 2007 and 2017, six hurricanes impacted Mahahual, Felipe Carrillo Puerto, Bacalar, and Quintana Roo municipalities where Uaymil protected area is located (INEGI, 2016). Studies by Zheng *et al.* (2023), Ren *et al.* (2022), and Zhang *et al.* (2023) indicated that high elevation, temperature, and precipitation adversely affect EQI. In Quintana Roo, climatic variables have been on the rise since 1986 (De la Barreda *et al.*, 2020). These factors, along with others mentioned, could be primary drivers contributing to the changes and patterns observed in Uaymil as reported by this study.

Despite these challenges and the presence of deforestation and degradation drivers, Uaymil's ecosystems have shown resilience. Increases in the mean values of each ecological indicator, maintenance of high vegetation coverage, productivity, leaf cover, and an increase in the surface area of high to very high EQI categories demonstrate the ecological quality and resilience of the area. This resilience is essential for biodiversity conservation and the provision of ecosystem services.

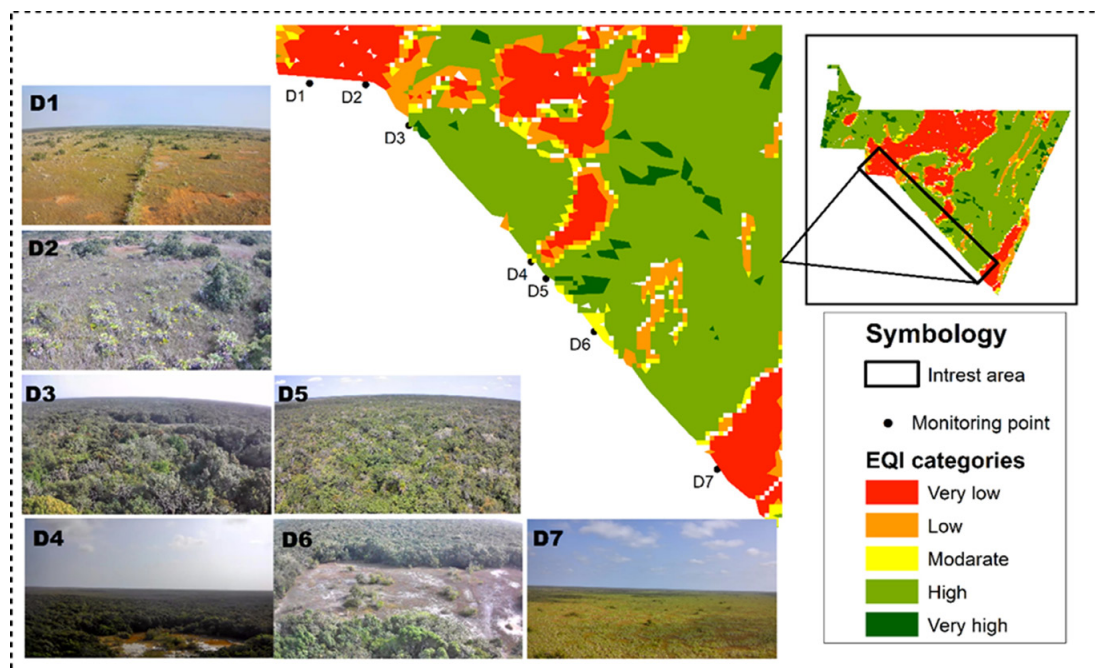
### **3.4. Ecosystem quality index: benefits and limitations**

EQI has highlighted the overall high resilience, and the current state of the vegetation types, by identifying areas for further analysis and potential restoration activities. The EQI allows for monitoring and identifying areas that have experienced vegetation loss and those with no vegetation cover, which require further analysis. In addition, the temporal analysis of changes in EQI could help us determine influencing factors that contribute to the degradation of ecosystem quality. For example, Zhang *et al.* 2023 used EQI to evaluate degradation within forests, grasslands, wetlands, and farmlands. They identified that grasslands, farmlands, and wetlands presented low quality and a reduction in EQI over the last 20 years, due to an increase in economic growth and an over exploitation of fishery resources. This resulted in increased pollution, habitat destruction, and overuse of natural resources. In contrast, forest ecosystems presented the opposite

trend, with forest management and returning farmland to forest improving quality. Other studies also emphasize the potential of EQI for the evaluation of ecosystems. Wang *et al.* (2022) and Zheng *et al.* (2023) noted that EQI, when combined with other spectral vegetation indicators through a pressure-state-response analysis, is a fundamental approach for evaluating ecosystems and identifying degradation factors. In addition, it aids in ecological zoning of key conservation areas, and potential restoration zones.

Nevertheless, EQI has several limitations. For instance, vegetation indices may not adequately account for the quality and productivity of diverse ecosystems such as mangroves, savannas, and wetlands. This is related to poor vegetation coverage, low LAI characteristics, and the presence of water, which can lead to underestimations and misinterpretations due to the variability in conditions in these ecosystems influenced by climatic, soil, and water levels (Gao, 1996; Tran *et al.*, 2022). Secondly, ecological indicators (LAI, GPP, and FVC) may exhibit distinct variations in response to distinct vegetation type, and climatic, seasonal or degradation factors. For example, Zhang *et al.* (2023) found 33.2% to 35.0% mismatch phenological difference between indicators, which means each ecological indicator responds to climatic or environmental factors differently. Additionally, they reported a 10-day difference in identifying phenological changes using these indicators. This indicates that each indicator may detect seasonal changes at different times, showing changes up to 10 days earlier or later than others. Thirdly, using low spectral resolution images excludes finer details and small patches of degradation areas within these ecosystems (Xu *et al.*, 2021). For instance, Figure 6 shows image D4, which represents patches of degraded areas where construction material extraction occurred, however these areas were classified as having a moderate EQI. This output could be due to the low resolution of the used images, and the weighted reflectance average of the small degraded patch and its surrounding vegetation.

Other limitations would be obtaining high-quality images, especially in the tropics where there is a presence of high cloud cover throughout the year. Additionally, the categorization of each



**Figure 6.** Conservation status on Uaymil protected area of flora and fauna. Image D1 represents the marsh ecosystem which presents a high coverage of species within the *Cyperaceae* family, and patches of vegetation known as wetland forest. D2 is a representation of grassland patches with high coverage of *Acoelorrhapha wrightii* (Griseb and Wendl) H. Wendl. ex Becc. with species from the *Poaceae* family. D3 and D5 present forest vegetation with high ecosystem quality and dense vegetation coverage. D4 and D6 present ecosystem degradation due to the extraction of material within Uaymil protected area. D7 is a representation of mangrove ecosystems.

EQI level has not been standardized to reflect the conditions observed in the field, which may affect the assessment accuracy. However, these limitations could be reduced by considering the characteristics of each ecosystem type analysed and their response to different environmental, social, and economic influencing factors. Furthermore, using high resolution satellite images for analysing ecosystem quality, integrated with field evaluation or utilizing UVA (unmanned aerial vehicles), could be an excellent tool used to accurately determine traits of degradation within ecosystem types.

Future research directions should be aim at developing or improving EQI tailored to distinct ecosystems like mangroves, savannas, and wetlands. In addition, establishing standardized frameworks for EQI categorization through field validation and local calibration will ensure precision and relevance.

#### 4. Conclusion

This study demonstrates the value of using multiple indicators to analyse the spatial-temporal dynamics of ecosystems and highlights the importance of the EQI in assessing vegetation conservation status. It also provides insights into ecosystem resilience and the current condition of ecosystems within the Uaymil PA.

The ecological indicators LAI, GPP, and FVC show positive correlations with each other and strongly influence the EQI in the Uaymil PA. This integration enhances the EQI's ability to reflect changes, improvements, or declines in ecosystem quality. Spatial-temporal changes in vegetation types were observed due to fluctuations in the mean values of LAI, GPP, FVC, and EQI, with notable shifts in 2005, 2011, 2015, and increases in all indicators in 2000, 2011, and 2023. These trends suggest that Uaymil ecosystems have a high resilience to degradation factors and are generally in a favourable state.

Low values of ecological indicators and EQI are primarily found in mangrove and marsh ecosystems, which naturally have lower vegetation coverage and productivity compared to forests. This is a characteristic of these ecosystems and not indicative of poor health. Therefore, identifying areas with low EQI within forest ecosystems enhances the index ability to detect reduced vegetation, productivity, and leaf area, which may be caused by degradation factors and warrant further analysis and potential restoration efforts.

In conclusion, the Uaymil PA is characterized by large vegetation cover, leaf area, productivity, and ecosystem quality, indicating a favourable state and high conservation priority.

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