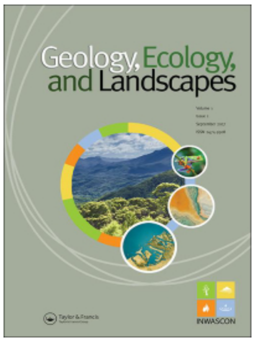

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Analyzing ecosystem functions in Bangladesh's forests: a historical MODIS study

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ABSTRACT

The accelerating degradation and damage of forest ecosystems worldwide due to human activities represent a pressing concern. This is particularly evident in Bangladesh, where the majority of terrestrial biodiversity is concentrated within forest ecosystems. Our study explores four ecosystem functions and nine indicators such as net primary productivity (NPP), gross primary productivity (GPP), land surface temperature (LST), enhanced vegetation index (EVI), leaf area index (LAI), normalized difference vegetation index (NDVI), evapotranspiration (ET) and potential evapotranspiration (PET). These elements were assessed using MODIS remote sensing data gathered from four co-managed forest protected areas (CFPA) and two bio-diverse non-co-managed forest areas (BNCFA) from 2002 to 2020. While co-management activities in CFPAs aim to conserve biodiversity, reduce local costs, and promote equitable management, BNCFAs function without such collaborative management efforts. Our findings revealed statistically similar ecosystem functions and their indicators across CFPAs and BNCFAs (t-test, $p > 0.05$). Seasonal patterns of ecosystem functions also show similar patterns. Interestingly, despite concerted efforts and special initiatives, CFPAs did not exhibit superior ecosystem functions when compared to BNCFAs. In conclusion, our study indicates that ecosystem functions have exhibited similarities across both spatial and temporal scales in the two management regimes.

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KEYWORDS
Ecosystem functions; remote sensing; co-management; reserve forest; village common forest; homestead forest

Introduction

Anthropogenic activities are rapidly degrading forest ecosystems, causing global biodiversity loss and destruction of natural resources (Subroto et al., 2017). Forests are critical ecological reservoirs and major economic lifelines (Jashimuddin & Inoue, 2012). To mitigate this degradation, many developing nations, including Bangladesh, have adopted co-management strategies for protected areas (PAs), seeking to reconcile conservation with local livelihoods (A. Z. M. M. Rashid et al., 2017). However, these strategies are not always effective, due to unequal power distribution, lack of decision-making decentralization, and limited benefit-sharing arrangements (Subroto et al., 2017).

Interestingly, other forest management types, such as reserve forests and community-based forests, have received less attention despite their potential significance in maintaining ecosystem functions over time. This points to the need for a thorough understanding of ecosystem functions under different management regimes, such as co-managed forest protected areas (CFPAs) and Bio-diverse non-co-managed forest areas (BNCFAs).

As one of the global hotspot for biodiversity, Bangladesh offers a unique context for this investigation. Its forest areas host an abundant terrestrial biodiversity, offering various ecosystem services crucial for our living standards and climate change adaptation. However, due to anthropogenic activities, overexploitation, and a historical emphasis on timber and non-timber products, these forests are under threat (M. M. Rashid, 2001). Despite attempts to address this via PAs and co-management strategies, the effectiveness of these measures remains questionable (Subroto et al., 2021).

Consequently, a comprehensive assessment of our ecosystem is critical for informed, sustainable policymaking and management decisions. Key to this assessment is understanding the role of BNCFAs in maintaining ecosystem functions and overall forest health. However, previous studies have been limited to cross-sectional analyses, lacking the necessary spatio-temporal data to reflect the true health of our forests (Pettorelli et al., 2017). Addressing this gap is pivotal to devising effective conservation strategies and achieving sustainable goals (Pettorelli et al., 2017).

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This paper employs multiple ecosystem function analyses, utilizing innovative remote sensing technologies such as Essential Biodiversity Variables (EBVs), to address gaps in biodiversity and ecosystem function monitoring (Pettorelli et al. 2017). Satellite remote sensing, specifically the Moderate Resolution Imaging Spectroradiometer (MODIS), offers high-resolution, continuous global data, enabling efficient decision-making (Pettorelli et al., 2017; Senna, 2005).

The study's objectives include historical analyses of ecosystem functions across six distinct areas in Bangladesh, assessing the effectiveness of CFPAs and BNCFAs over the past 19 years. The investigation targets several ecosystem functions, such as climate regulation, pollination regulation, and energy regulation, via a range of indicators.

Unlike previous studies that took cross-sectional approaches (K. N. Islam et al., 2021; Jashimuddin et al., 2021), this work employs longitudinal study design, thereby capturing the ecosystem functions' dynamic nature and evaluating various forest management regimes' effectiveness. The hypothesis is that BNCFAs are as essential in maintaining ecosystem function as co-managed PAs. In light of this, it is imperative to understand ecosystem functions under different management regimes to prevent biodiversity loss, ecosystem damage, and acknowledge BNCFAs' significant role.

Methodology

Study area and its selection criteria

The study encompasses both CFPAs and BNCFAs, located in the Hill Forest areas of Bangladesh (Figure 1 and Figure S1), characterized by moist tropical evergreen and semi-evergreen forests. Typical species include *Artocarpus chaplasha*, *Dipterocarpus* spp., *Syzygium* species, *Lagerstroemia* speciosa, and others. Average temperatures range from 20°C to 30°C, peaking at 35°C in summer (May to September), with heavy rainfall during the monsoon season (June to September) (Ghimire et al., 2022; Huffman et al., 2015; NOAA, 2020).

The study focuses on four co-managed protected forests (Satchari, Rema-Kalenga, Chunati, Lawachara) and two non-co-managed areas (Khagrachari and Bandarban). These regions comprise various land uses, including common property resource forests (VCFs), reserved forests, and homestead forests, along with other land uses in Khagrachari and Bandarban of Bangladesh (Figure 1; Table 1). Case study areas were selected purposively. CFPAs considered in this study were one of the oldest PAs considered for co-management intervention by the government (NSP, 2003). In the case of BNCFAs, the Khagrachari and Bandarban region of the Chittagong Hill Tracts (CHTs) were considered since these CHTs account for over 40% of Bangladesh's total forested area, is one of the country's

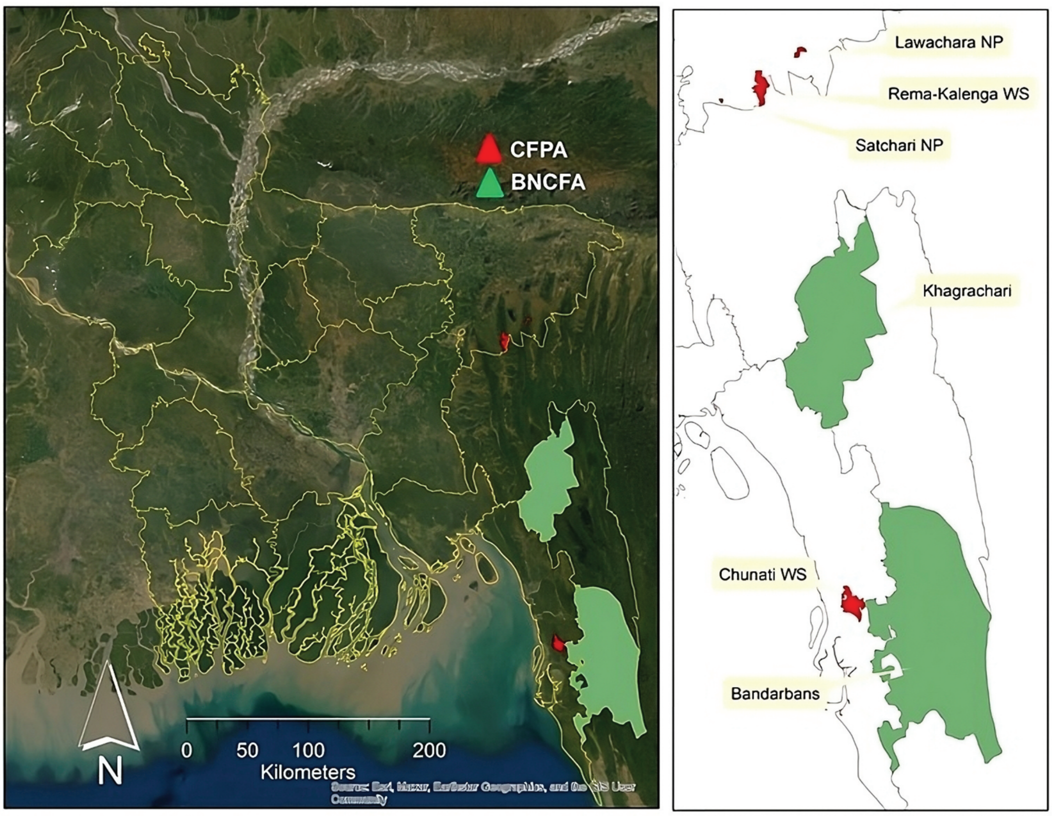

Figure 1. Map showing location of co-managed and non-co-managed forest areas.

Table 1. A brief summary of the study areas.

Protected areas	Ecosystem	Area (km^2)	Time of Designation	Location
Satchori National Park*	Mixed Evergreen	2.43	2005	Habigonj
Lawachara National Park*	Mixed Evergreen	12.5	1996	Moulvibajar
Rema kalinga Wildlife sanctuary*	Tropical evergreen and semi ever green	17.95	1980	Habiganj
Chunati Wildlife Sanctuary*	Tropical semi evergreen	77.63	1986	Chittagong
Khagrachori district**	Tropical Wet Mixed	4,479	-	Khagrachori
Bandarban district**	Tropical Evergreen and Semi Evergreen	2749	-	Bandarban

n.b. *indicates CFPA and **indicates BNCFA

most ecologically varied regions (UN-REDD, 2021). Regarding unequal sample size (large BNCFAS and small CFPAs area), in satellite image analysis using remote sensing techniques, ecosystem functions are calculated based on pixel values. Each pixel corresponds to one square kilometer or 500 m of the area being analyzed (Table 2) and holds a specific value. The MODIS system considers the average of the highest pixel values, and when downloading processed data from the NASA website, a single value is provided for each polygon, incorporating all the averaged pixels. As a result, the impact of area size is not very significant since the final value represents a composite of various pixel averages. Moreover, comparing the box plot graphs (Figures 3, 4 and supplementary material −3) for the inter quartile range, it can be observed that the sample sizes for different areas do not vary significantly in their pixel values for the ecosystem functions CFPAs and BNCFPAs.

The BNCFAs, managed by indigenous communities without governmental control, encompass varied land uses including VCFs, reserved forests, and homestead forests. These areas provide unique forest ecosystems and livelihoods for local communities (Miah & Ahmed, 2013; Uddin et al., 2020). However, the forest cover in these areas is declining (Muzaffar et al., 2011). Homestead forests contribute significantly to carbon sequestration, fuel wood supply, and food production while supporting rural economies, ecosystem conservation, and reducing emissions (Baul et al., 2021). Yet, over exploitation and land use conversion are leading to their fragmentation (Baul et al., 2021). The BNCFAs also include other land uses like built-up and aquatic areas.

Methods

Ecosystem functions, indicators, and MODIS products

This study employs MODIS-based products to analyze ecosystem function dynamics purposively chosen to assess forest management practices' efficacy. MODIS has emerged as one of the most widely used imaging tools in ecology and conservation studies. A comprehensive search on the Scopus database, using the keywords "MODIS AND image* AND (ecosystem function)" from 2015 to 2022, resulted in approximately 7500 published research articles in indexed journals (Fig. S2). Researchers frequently employed MODIS data to investigate various aspects of ecosystem structure and functions, including vegetation greenness, evapotranspiration, hydrology, phenology, gross primary production, wildfires, agriculture, albedo, land surface temperature, leaf area index, among many others (Supplementary material 1, Fig. S2). The abundance of research using MODIS data highlights its significance in advancing our understanding of ecological processes and conservation efforts. A brief description of the parameters considered for this study is given below:

- Gross Primary Productivity (GPP), which measures CO2 fixed by vegetation through photosynthesis, contributing to the terrestrial carbon cycle and influencing ecosystem services like fuel, food, and fiber production. Changes in GPP can impact atmospheric anthropogenic carbon dioxide levels (Verma et al., 2014; Wang et al., 2017).

Table 2. A list of ecosystem functions, indicators, and MODIS products.

Ecosystem Functions	Indicators	Products	MODIS product resolution	Product source
Water Regulation	Evapotranspiration (ET)	MOD16A2.061	500 m	Running et al. (2021a)
	Potential Evapotranspiration (PET)	MOD16A2.061	500 m	Running et al. (2021b)
Temperature regulation	Land Surface Temperature (LST)	MOD21A2.061	1 km	Hulley and Hook (2021)
	Land Surface Temperature (LST)	MOD11A2.061	1 km	Wan et al. (2021)
	Fraction of Photosynthetically Active Radiation (FPAR)	MOD15A2H.061	500 m	Myneni et al. (2021)
Ecosystem productivity regulation	Gross Primary Productivity (GPP)	MOD17A2H.061	500 m	Running et al. (2021a)
	Net primary Productivity (NPP)	MOD17A3HGF.061	500 m	Running and Zhao (2019)
Biomass and carbon regulation	Leaf Area Index (LAI)	MCD15A2H.006	500 m	Didan (2021)
	Enhanced Vegetation Index (EVI)	MOD13A1.061	500 m	Didan (2021)
	Normalized difference vegetation index (NDVI)	MOD13A1.061	500 m	Didan (2021)

- Net Primary Productivity (NPP), derived from the difference between carbon fixed by autotrophs and the carbon remaining after respiration. NPP reflects the conversion of light energy and material in the terrestrial ecosystem, playing a crucial role in vegetation dynamics and overall ecosystem health (Wang et al., 2022).
- Vegetation Indices (VIs), indispensable for comprehending different vegetation categories, their characteristics, and their spatial-temporal variations. This study uses two VI products: Normalized difference vegetation index (NDVI) and Enhanced Vegetation Index (EVI). Both indices aid in monitoring photosynthetic vegetation activity globally (Didan et al., n.d.).
- Leaf Area Index (LAI), which estimates leaf area, crucial for studying primary production, plant-soil -water relations, light reflectance, and heat transfer, among other factors (Pandey & Singh, 2011).
- Fraction of Photosynthetically Active Radiation (FPAR), measuring the PAR absorbed by photosynthetic tissues, influencing energy, mass, and momentum exchanges between the canopy and the atmosphere (Senna 2005).
- Land Surface Temperature (LST), a proxy for land surface air temperature, influenced by anthropogenic activities, is essential for analyzing climatic changes (Jaber & Abu-Allaban, 2020).
- Evapotranspiration (ET), the amount of water evaporated from a surface, is a vital component of the hydrological cycle and is crucial for water resource allocation in agriculture (Elnashar et al, 2021; Salehnia et al, 2018).
- Potential Evapotranspiration (PET), the maximum evaporation from a well-watered surface, is needed to understand climate change effects on terrestrial ecosystems and plan agriculture and water resource management (Kim and Hogue, ; Salehnia et al., 2018). Detailed calculations for each parameter are referenced in the respective cited literature (Table 2).

Data extraction process and data analysis

We obtained MODIS product data via the Application for Extracting and Exploring Analysis Ready Samples (AppEEARS), a user-friendly, web-based platform developed by NASA for processing satellite images (AppEEARS Team, 2022). We sourced polygons of co-managed Protected Areas (PAs) from Protected Planet (UNEP-WCMC, 2019) and the administrative boundaries of Khagrachori and Bandarban districts from Global Administrative Areas (2018). After obtaining these, we excluded co-managed PAs from BNCFA. NASA has validated all the MODIS products employed in this study through field observation, eliminating the need for additional field validation (https://modis-land.gsfc.nasa.gov/index.html#). Table 2 provides a detailed description of the ecosystem functions, while we adopted proxies and indicators from Pettorelli et al. (2017).

We conducted a time-series analysis of multiple ecosystem functions from 2002 to 2021, examining both annual and seasonal variations. Our study utilized box plot graphs, plotting the mean values of ecosystem parameters as response variables against the two different management regimes as the explanatory variable. We employed an independent sample t-test to assess the statistical differences in ecosystem functions between CFPA and BNCFA concerning annual and seasonal variations.

Moreover, we used simple linear regression to investigate the influence of vegetation parameters, such as NDVI, EVI, and LAI, on evapotranspiration, land surface temperature, and ecosystem productivity. To determine the strength of the relation between the indicators, we also performed a Pearson correlation test. Line plots helped visualize the temporal pattern of ecosystem function changes under different management regimes. Figure 2 presents a schematic diagram illustrating the data extraction methods used in this study.

Results

Ecosystem functions and properties differences under CFPA and BNCFA

Statistically significant differences exist between management regimes in terms of ecosystem parameters like ET, EVI, and LAI ($p < 0.05$). The PAs showed marginally higher median values for ET and LAI, suggesting slightly better conditions compared to BNCFA. However, the differences are minor, indicating similar ecosystem function status across the regimes. Conversely, the EVI parameter showed significantly higher medians in BNCFA, signifying more vegetation greenness. For GPP, NDVI, LST, and PET parameters, no significant statistical difference was noted ($p > 0.05$), affirming that overall, ecosystem conditions do not significantly differ between PAs and BNCFAs. This supports our study's hypothesis, confirming similar ecosystem statuses in CFPA and BNCFA (Figure 3), despite PAs being explicitly created for conservation (Figure 3, Supplementary Material 3).

In the dry season, LST, PET, EVI, and GPP parameters showed a significant difference ($p < 0.05$). While BNCFAs had slightly higher median values for EVI, PET, and GPP, suggesting marginally better conditions, CFPA had a higher median for LST, indicating higher land surface temperature. However, ET, LAI, NDVI, and FPAR parameters showed no significant difference, suggesting similar ecosystem conditions between CFPAs and BNCFAs within the dry season (Figure 4).

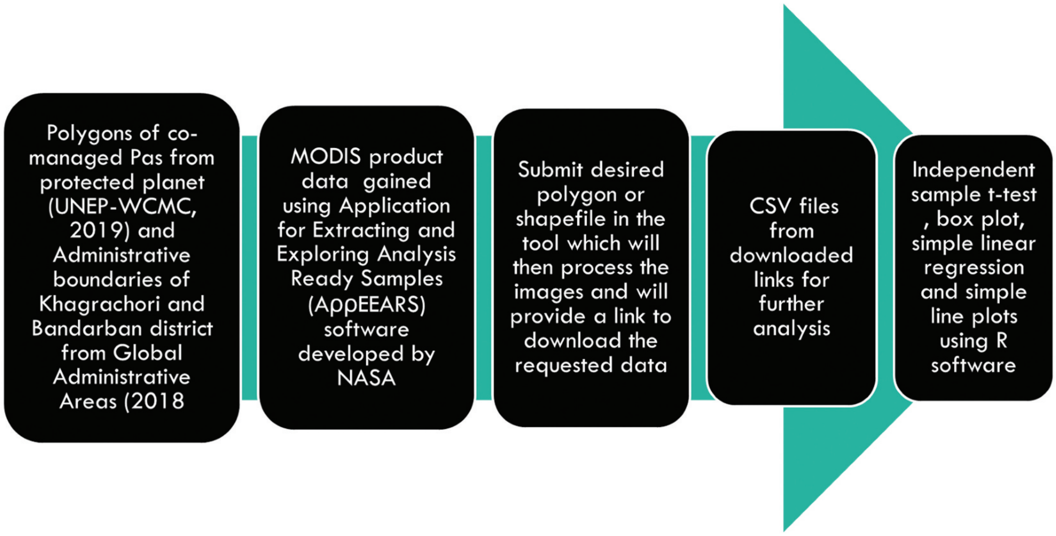

Figure 2. Method of data extraction and analysis.

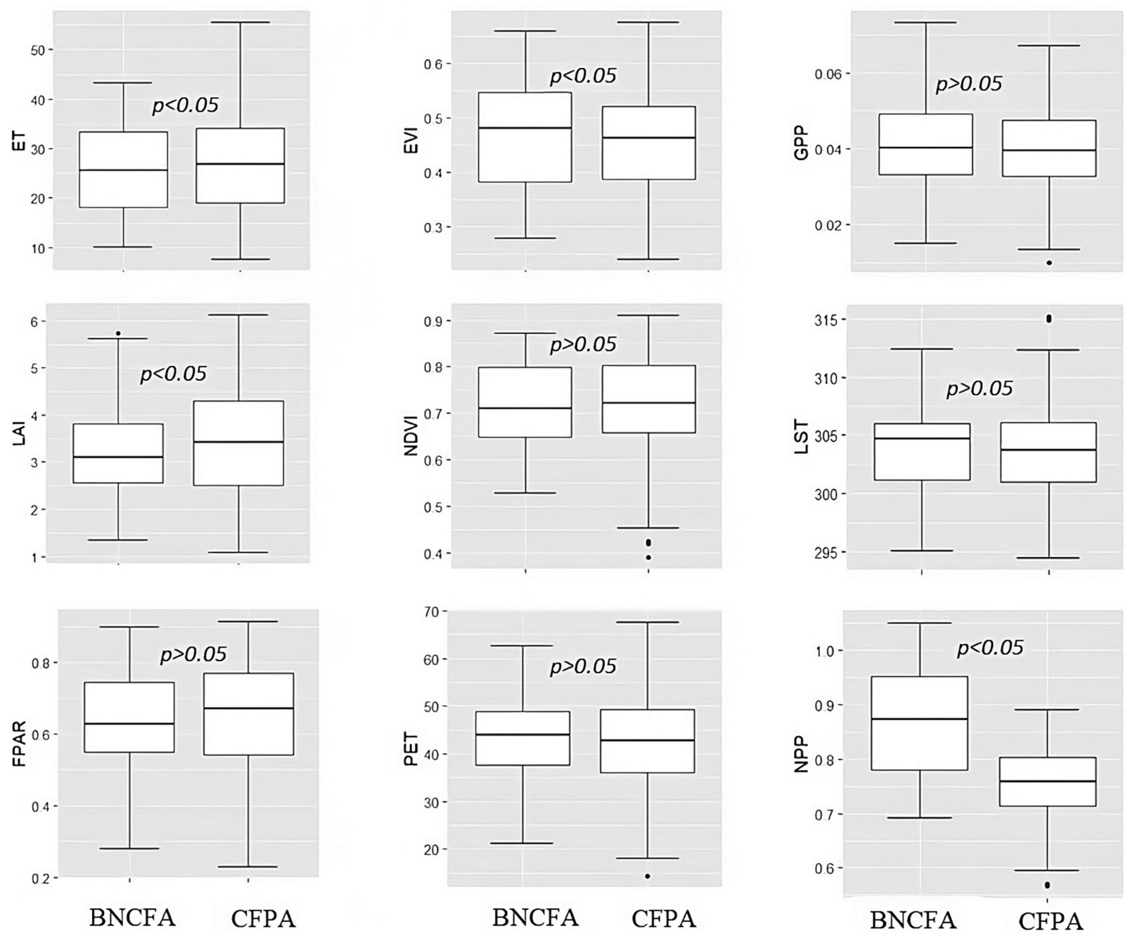

Figure 3. Differences in ecosystem functions under CFPA and BNCFA. t-test has been conducted to see the differences between CFPA and BNCFA.

For the wet season, LAI, LST, ET, and PET parameters varied significantly between the regimes ($p < 0.05$). CPFAs displayed higher median values for LAI, ET, and PET, indicating marginally better conditions. However, the higher LST in CPFAs despite the larger leaf area index may imply poorer vegetation quality, warranting further research. No significant difference was noted for EVI, NDVI, GPP, and FPAR parameters (Figure 4), again underscoring similar ecosystem conditions between CPFAs and BNCFAs. The annual temporal variation of MODIS NPP precludes seasonal variance analysis. This analysis validates the hypothesis, confirming comparable ecosystem function statuses in both CFPA and BNCFA throughout the seasons, despite marked differences between wet and dry seasons due to climatic variation.

Influence of vegetation on ecosystem functions

Water regulation nexus with vegetation indices

The positive correlation between vegetation indices and ET was consistent across protected and non-protected areas, highlighting the uniformity in ecosystem functioning across different management regimes. The regression between ET and LAI ($R^2 = 0.24$, $p < 0.05$), EVI ($R^2 = 0.62$, $p < 0.05$), NDVI ($R^2 = 0.008$, $p < 0.05$) shows a significant relationship, with LAI and EVI effectively explaining the response parameter variance. Conversely, PET displayed negative relationships with EVI and NDVI but a positive one with LAI. The significant regression between PET and LAI ($R^2 = 0.01$, $p < 0.05$), NDVI ($R^2 = 0.008$, $p < 0.05$) underscores their positive relationship. Overall, there's no significant difference in water regulation functions ET and PET under the two management regimes Figure 5(a).

Temperature regulation nexus with vegetation indices

The inverse relationship between LAI, EVI, NDVI, and LST shows vegetation's influence on temperature regulation is similar across management regimes. Notably, there's a statistically significant relationship between LST and LAI ($R^2 = 0.009$, $p < 0.05$), EVI ($R^2 = 0.001$, $p < 0.05$), NDVI ($R^2 = 0.06$, $p < 0.05$). FPAR's significant relationship with LAI ($R^2 = 0.56$, $p < 0.05$), EVI ($R^2 = 0.02$, $p < 0.05$) and NDVI ($R^2 = 0.52$, $p < 0.05$) shows increasing FPAR with rising vegetation indices across both CFPA and BNCFA Figure 5(b).

Ecosystem productivity nexus with vegetation indices

The positive trend between vegetation indices and GPP, along with the significant relationship between GPP and LAI ($R^2 = 0.24$, $p < 0.05$), EVI ($R^2 = 0.62$, $p < 0.05$), NDVI ($R^2 = 0.008$, $p < 0.05$), demonstrates that vegetation indices effectively explain GPP variance across management regimes. NPP also shows a positive trend with increasing vegetation, evidenced by the significant relationship between NPP and LAI ($R^2 = 0.07$, $p < 0.05$), EVI ($R^2 = 0.30$, $p < 0.05$) and NDVI ($R^2 = 0.12$, $p < 0.05$). Despite a declining trend in NPP for LAI in CPFAs, overall ecosystem productivity (GPP and NPP) is similar across both forest management regimes.

During the dry season in both CFPA and BNCFA, vegetation indices NDVI, EVI and LAI has strong positive correlation with ET, FPAR and GPP. However, have an weak relationship with LST and PET in the case of CFPA. Whereas, vegetation parameters has inverse relation with LST in BNCFA indicating positive cooling effect (Tables 3 and 4).

In the wet season, ET and LST decrease as vegetation indices increase and the remaining parameter has positive relation in CFPA. In contrast, LST and PET has inverse relation with vegetation indices in BNCFA (Tables 5 and 6).

Temporal changes (2002–2021) of ecosystem functions

Yearly changes of ecosystem functions

ET began higher in CFPAs than BNCFAs, experienced fluctuations, and eventually declined to roughly

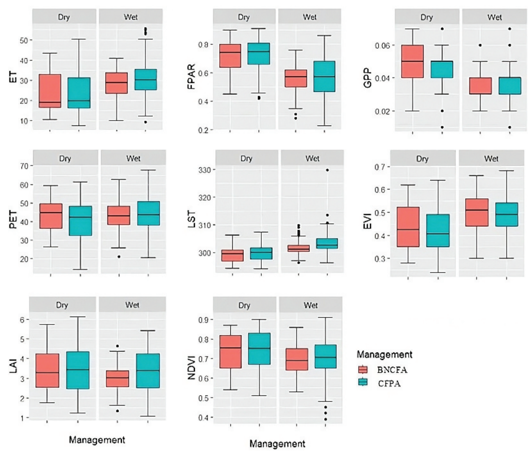

Figure 4. Seasonal variations of differences in ecosystem functions under CFPA and BNCFA. t-test has been conducted to see the differences between CFPA and BNCFA.

20 kg/m^2 in both regimes (Figure 6). PET initially followed ET's trend, with later improvements in BNCFAs. Its decline mirrored ET, settling around 44 kg/m^2 in BNCFAs and below 42 kg/m^2 in CFPAs.

EVI started positively but saw rapid declines, with worst conditions around 2010. Despite an overall better condition in BNCFAs, recent years show a slight improvement in CFPAs. NDVI started well but worsened around 2010, declining further towards the study's end in both regimes.

LAI began in excellent condition in both regimes but declined over time. It deteriorated more in BNCFAs, yet showed a slight increase in CFPAs towards the end. FPAR began with an upward trend, experienced a dip around 2010, but ended better in CFPAs.

GPP started positively, dipped around 2010, and eventually declined to around 0.04 kg C/m^2 in both regimes, with BNCFAs maintaining better conditions throughout. NPP mirrored GPP's trend, with better conditions in BNCFAs, and both regimes saw a decline towards the study's end.

LST started low, peaked around 2015, and reached an all-time high by the study's end in both regimes. Over the study period, ET, NDVI, LAI, and FPAR were in better condition in CFPAs, while EVI, GPP, NPP, and PET fared better in BNCFAs. Most parameters reached their worst around 2010, with general deterioration observed towards the end of the period.

Monthly changes of ecosystem functions

Monthly fluctuations in ecosystem properties were similar in CFPA and BNCFA areas. ET started low, below 20 kg/m^2, peaked above 35 kg/m^2 in the 10th month, and then declined to around 20 kg/m^2. PET began around 35 kg/m^2, peaked above 50 kg/m^2 between the 2nd and 5th months, then declined to 35 kg/m^2 in BNCFAs and below 30 kg/m^2 in CFPAs.

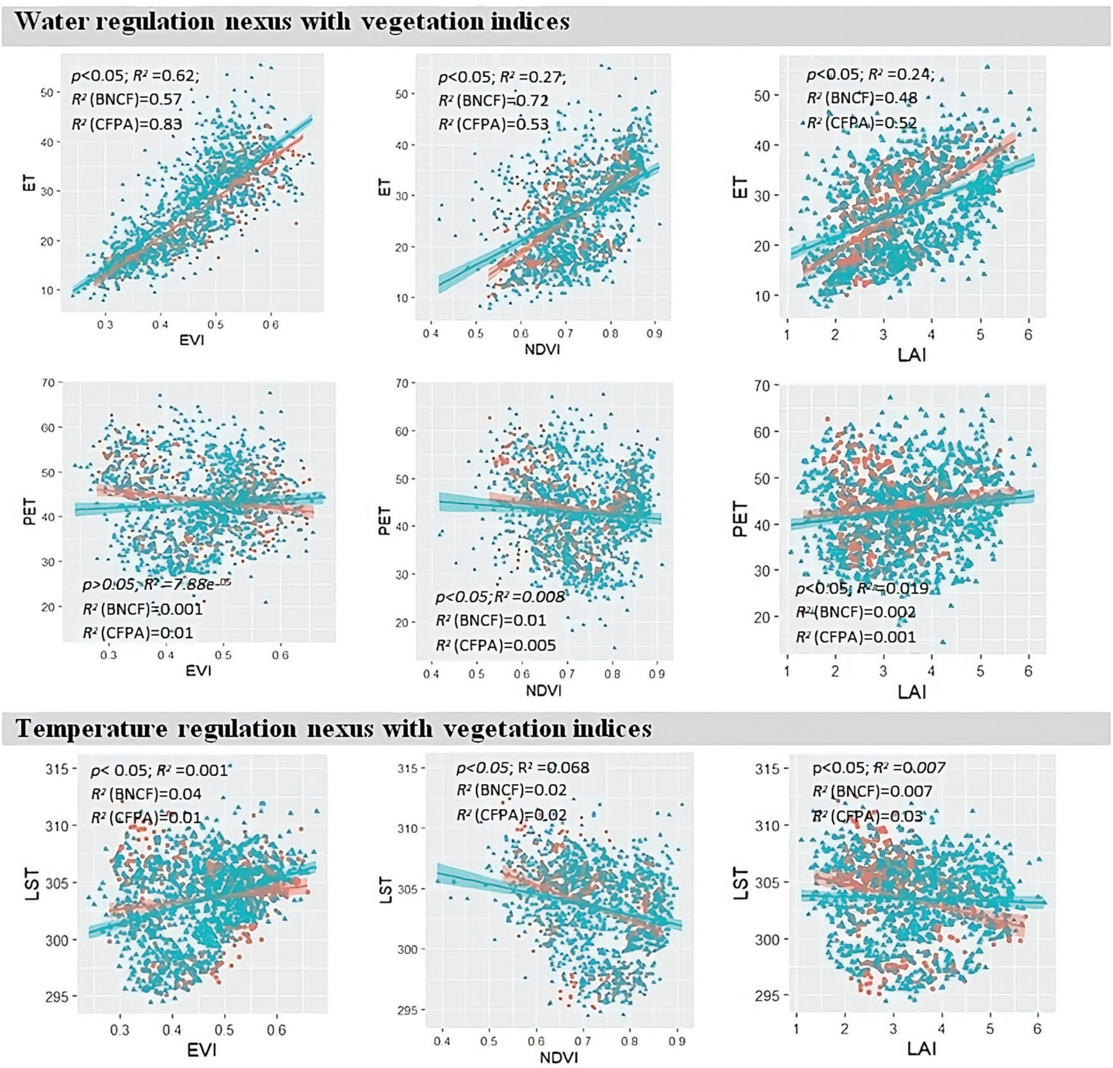

Figure 5a. Influence of vegetation on water, temperature, and ecosystem productivity regulation under different forest management regimes. Diagnostic plots of regression are available in supplementary material 1. Among three R^2 values, two values corresponds to BNCFA and CFPA, and another R^2 value represents combined datasets of BNCFA and CFPA.

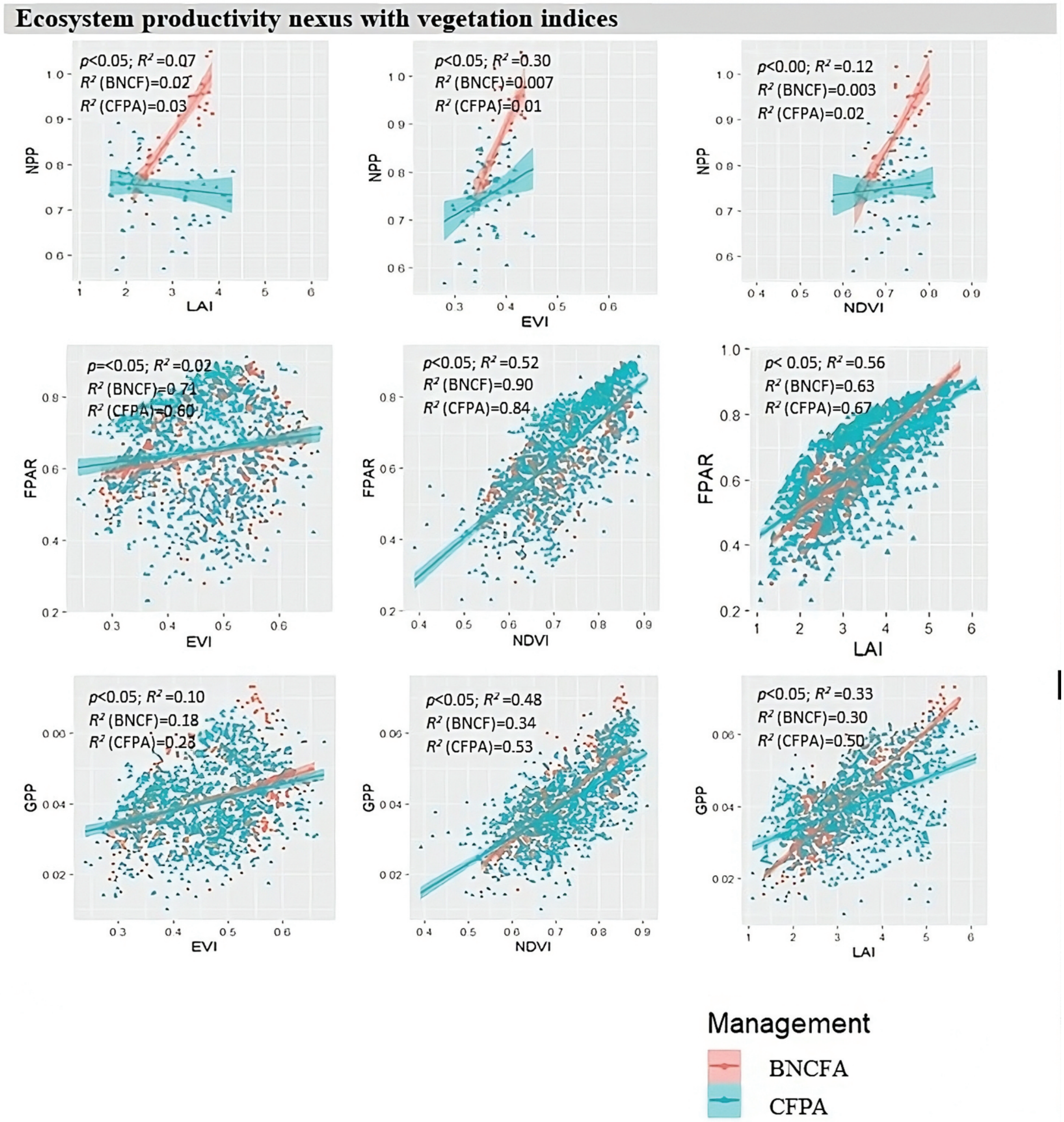

Figure 5b. (Continued).

Table 3. Pearson correlation of ecosystem function parameters in CFPA in dry season.

	LAI	FPAR	ET	LST	NDVI	GPP	PET	EVI
LAI	1.00	**0.89**	**0.97**	0.24	**0.92**	**0.82**	0.22	**0.98**
FPAR	0.89	1.00	**0.80**	−0.19	**0.97**	**0.94**	−0.18	**0.92**
ET	0.97	0.80	1.00	0.36	**0.85**	**0.79**	0.39	**0.95**
LST	0.24	−0.19	0.36	1.00	−0.16	−0.21	**0.97**	0.10
NDVI	0.92	0.97	0.85	−0.16	1.00	**0.92**	−0.15	**0.97**
GPP	0.82	0.94	0.79	−0.21	0.92	1.00	−0.14	**0.85**
PET	0.22	−0.18	0.39	0.97	−0.15	−0.14	1.00	0.09
EVI	0.98	0.92	0.95	0.10	0.97	0.85	0.09	1.00

LAI initially dropped around 3.0 m^2/m^2, peaked over 4.50 m^2/m^2 in the 10th month, then declined to about 3.50 m^2/m^2. FPAR started at approximately 0.7%, peaked above 0.8% in the 10th month, hit its lowest at under 0.5% in the 7th month, and finally declined to roughly 0.70%.

EVI and NDVI initially decreased, reaching their lowest points around the 2nd month. They peaked around the 10th month, with EVI above 0.5 and NDVI around 0.85, then declined again. GPP started around 0.05 kg C/m^2, hit its lowest between the 2nd

Table 4. Pearson correlation of ecosystem function parameters in CFPA in wet season.

	LAI	FPAR	ET	LST	NDVI	GPP	PET	EVI
LAI	1.00	**0.97**	**−0.52**	−0.11	**0.73**	0.05	**0.53**	0.06
FPAR	0.97	1.00	**−0.53**	0.06	**0.72**	0.07	**0.67**	−0.02
ET	−0.52	−0.53	1.00	**−0.59**	0.17	**0.80**	**−0.65**	**0.80**
LST	−0.11	0.06	−0.59	1.00	**−0.52**	**−0.61**	**0.72**	**−0.87**
NDVI	0.73	0.72	0.17	−0.52	1.00	**0.70**	0.14	**0.67**
GPP	0.05	0.07	0.80	−0.61	0.70	1.00	−0.28	**0.91**
PET	0.53	0.67	−0.65	0.72	0.14	−0.28	1.00	**−0.54**
EVI	0.06	−0.02	0.80	−0.87	0.67	0.91	−0.54	1.00

Table 5. Pearson correlation of ecosystem function parameters in BNCFA in dry season.

	LAI	FPAR	ET	LST	NDVI	GPP	PET	EVI
LAI	1.00	**0.92**	**0.95**	−0.23	**0.96**	**0.85**	−0.01	**0.98**
FPAR	0.92	1.00	**0.75**	**−0.57**	**0.95**	**0.96**	−0.36	**0.88**
ET	0.95	0.75	1.00	0.02	**0.87**	**0.70**	0.23	**0.96**
LST	−0.23	−0.57	0.02	1.00	−0.45	**−0.61**	**0.96**	−0.22
NDVI	0.96	0.95	0.87	−0.45	1.00	**0.89**	−0.26	**0.97**
GPP	0.85	0.96	0.70	−0.61	0.89	1.00	−0.37	**0.80**
PET	−0.01	−0.36	0.23	0.96	−0.26	−0.37	1.00	−0.02
EVI	0.98	0.88	0.96	−0.22	0.97	0.80	−0.02	1.00

Table 6. Pearson correlation of ecosystem function parameters in BNCFA in wet season.

	LAI	FPAR	ET	LST	NDVI	GPP	PET	EVI
LAI	1.00	**0.85**	**0.63**	−0.30	**0.95**	**0.81**	−0.13	**0.68**
FPAR	0.85	1.00	0.17	0.21	**0.70**	**0.51**	0.40	0.24
ET	0.63	0.17	1.00	**−0.92**	**0.81**	**0.91**	**−0.83**	**0.99**
LST	−0.30	0.21	−0.92	1.00	**−0.55**	**−0.72**	**0.96**	**−0.90**
NDVI	0.95	0.70	0.81	−0.55	1.00	**0.95**	−0.35	**0.86**
GPP	0.81	0.51	0.91	−0.72	0.95	1.00	**−0.54**	**0.93**
PET	−0.13	0.40	−0.83	0.96	−0.35	−0.54	1.00	**−0.77**
EVI	0.68	0.24	0.99	−0.90	0.86	0.93	−0.77	1.00

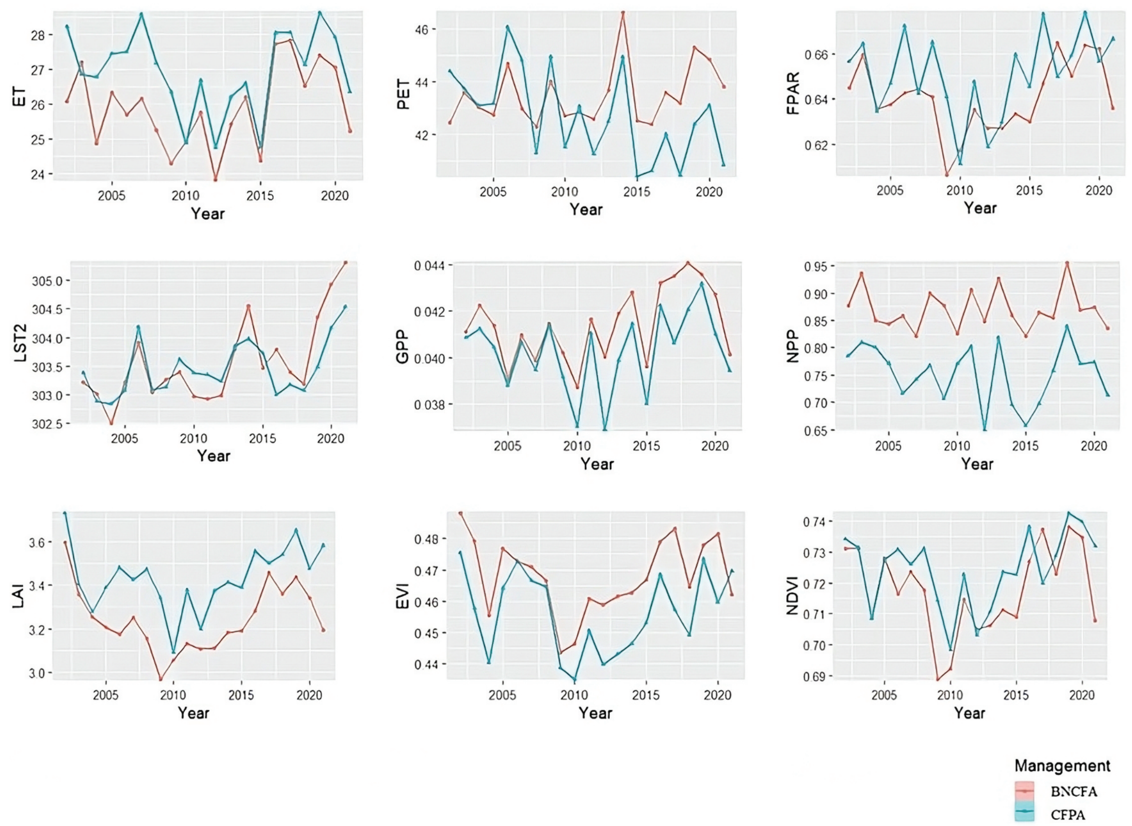

Figure 6. Temporal changes in ecosystem functions.

and 5th months, peaked at 0.06 kg C/m^2 in the 10th month, then declined to under 0.05 kg C/m^2.

LST began at its lowest, around 297.50 Kelvin, then increased rapidly to 307.50 Kelvin in both regimes before declining to around 297.50 Kelvin. Most parameters were in their best condition around the 10th month, with no significant pattern difference between BNCFAs and CFPAs observed over the years (Figure 7).

Discussion

Bangladesh boasts a rich natural ecosystem teeming with biodiversity. Significant forests found throughout the country create a terrestrial ecosystem abundant in plant and animal life. The escalating threat of deforestation, biodiversity loss, and ecosystem degradation have positioned efficient forest management as a global and national priority. Given Bangladesh's vulnerability to climate change consequences, forests play a crucial role in our global response (Jashimuddin & Inoue, 2012). However, much natural forest vegetation has been cleared for other human demands, such as agriculture. A 2015 FAO report declared Bangladesh as a forest-poor country, implying that forest ecosystems are endangered and on the brink of collapse. Consequently, they require immediate conservation and protection (Subroto et al., 2017).

About 16% of the world's terrestrial cover comprises protected areas (Geldmann et al., 2019), and Bangladesh has approximately 38 such areas (A. Z. M. M. Rashid et al., 2017). These protected areas aim to ensure proper ecosystem functionality, biodiversity conservation, and ecosystem service provision to communities. Despite calls to increase the number of protected areas worldwide (Zeng et al., 2022), attention must also be given to improving the productivity of existing protected areas. Co-management has been proposed as a solution to PA governance issues, addressing conservation predicaments and conflicts between central authorities and locals (Subroto et al., 2017). Co-managed protected areas are expected to be more bio-diverse and ecologically healthy than non-protected areas due to special initiatives by governmental and non-governmental organizations. However, BNCFA have largely been overlooked in strategies and management due to misconceptions regarding their ecological significance.

Analysis of four co-managed protected forests and two non-co-managed forest sites in Bangladesh yielded similar results, revealing no major differences in most ecosystem parameters between protected (i.e., CFPAs) and non-protected areas (i.e., BNCFAs). Although LAI and ET were significantly higher in CFPAs, vegetation density and health were better in BNCFAs, as indicated by higher EVI values. Furthermore, no significant differences were observed across different seasons in both forest types. However, NDVI didn't strongly correlate with ET, possibly due to errors in the NDVI product. On the contrary, EVI, which accounts for such errors, had a stronger relationship with land-based ET (Yebra et al., 2013).

Interestingly, ecosystem parameters representing ecosystem functions exhibited similar conditions in CFPAs and BNCFAs. In some cases, like vegetation health and density, non-co-managed forests performed better. This finding challenges the efficiency of co-managed protected forests given the resources invested in them. While no major differences were observed in the ecosystem parameters over the years, the data revealed a general decline in both co-managed protected forests and non-co-managed forests, suggesting our endangered ecosystem's worsening condition.

Co-management's main issues relate to the devolution of management and power to the local community. The top-down approach creates hurdles in shifting authority from the state level to the local community, leading to unequal benefit-sharing between the state government and locals. Despite some conservation successes, co-management hasn't been fully institutionalized, lacks legal policy, and has undefined procedures (Subroto et al., 2017).

Meanwhile, BNCFAs have been neglected, despite study results suggesting they are equally important for conservation and ecosystem richness. There is a significant lack of government and non-government organization effort towards BNCFAs. This neglect might increase mortality of several threatened species, cause habitat loss, and threaten breeding grounds. More research is required to understand these areas better.

The study revealed alarming observations of the condition of our ecosystem functions over the last 20 years. It underscores the urgent need for conservation before irreparable damage is done. The government should direct more focus on BNCFAs in terms of management, strategies, and investment. As this study indicates, some practices from these non-co-managed forests – VCFs, reserved forests, homestead forests – might be useful for enhancing the condition of co-managed protected forests. However, this suggestion necessitates further research for better understanding. Ultimately, we must properly understand ecosystem changes and the pressures impacting them to prevent further deterioration of Bangladesh's biodiversity and increasing ecosystem threats. Analyzing ecosystem

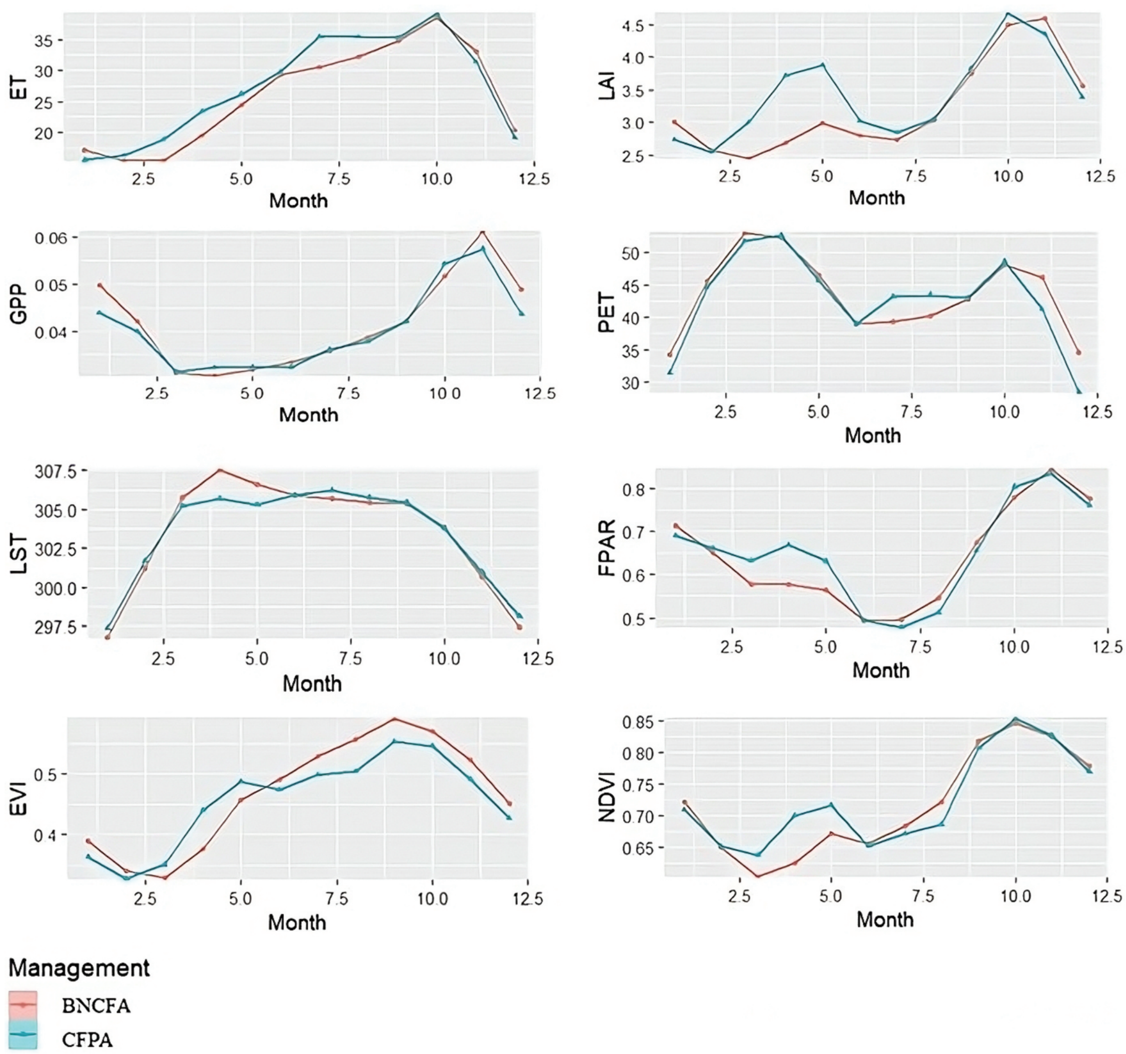

Figure 7. Monthly variation of ecosystem functions.

parameters as indicators of changes in ecosystems worldwide (Pettorelli et al., 2017) would aid this understanding, leading to informed management decisions.

Conclusion

The study finds that ecosystem functions across both co-managed and non-co-managed forest areas respond similarly over time and space, despite the special attention and initiatives by the Government towards the former. Non-co-managed forests have shown comparable ecosystem functions without such governmental interventions, which calls for a reassessment of current management practices. The government needs to focus on formalizing systems and strategies within these non-co-managed forests. Over the years, despite fluctuations, a concerning trend of deteriorating ecosystem conditions has emerged, underscoring the urgency for better management regimes. Some practices from non-co-managed forests, which have managed to maintain ecosystem functions effectively without special attention, could potentially be transferred to co-managed protected forests. However, this proposition necessitates further research. The study also reveals the interconnectedness of ecosystem parameters. While more research is warranted, analyzing these parameters can offer valuable insights into the overall ecosystem health. While MODIS data offers a more accessible option due to its availability of ecosystem parameter products, utilizing higher resolution satellite imagery like Sentinel or Landsat could yield increased accuracy. However, this approach becomes more complex as these higher resolution images currently lack the extensive ecosystem parameter products provided by MODIS. Therefore, there is a need for the development of similar products using higher resolution satellite imagery to enable more comprehensive investigations into ecosystem functions.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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