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Integrating remote sensing and in situ data to assess wetland ecosystem health within the Pressure-State-Response (PSR) framework in Lake Tana UNESCO Biosphere Reserve, Ethiopia

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ABSTRACT

The Lake Tana Biosphere Reserve (LTBR) consists of wetlands that provide critical ecosystem services but face degradation from anthropogenic pressures and climate change. This study integrates the Pressure-State-Response framework with multi-temporal remote sensing (Landsat and Sentinel2, 2011–2025) and participatory citizen science. Landscape metrics (patch density, Shannon diversity index, net primary productivity) were derived alongside demographic and infrastructure layers to assess pressures. Quantitative data were triangulated with focus group discussions and participatory mapping. Results show that high population density (up to 13,000 individuals/km²) and cultivated land expansion (78% to 85% from 2011 to 2025) are primary degradation drivers, manifesting as landscape fragmentation and declining vegetation productivity especially in the eastern floodplain areas of LTBR. Integrating spatial analysis with local knowledge reveals spatially differentiated wetland vulnerability shaped by demographic, agricultural, and climatic factors. This approach demonstrates the feasibility of fusing objective spatial data with participatory evidence, offering a scalable model for evidencebased conservation policy in the LTBR and other sensitive wetland systems.

KEYWORDS

- *Lake Tana Biosphere Reserve*
- *PSR Framework*
- *Remote Sensing*
- *Citizen Science*
- *Landscape Metrics*

Integration von Fernerkundungs- und In-situ-Daten zur Bewertung der Ökosystemgesundheit von Feuchtgebieten im Rahmen des Pressure-State-Response-(PSR) Modells im UNESCO-Biosphärenreservat Tanasee, Äthiopien.

ZUSAMMENFASSUNG

Das Biosphärenreservat Tanasee (LTBR) besteht aus Feuchtgebieten, die kritische Ökosystemleistungen erbringen, jedoch durch anthropogene Belastungen und den Klimawandel degradiert werden. In dieser Studie wurde das Pressure-State-Response-(PSR) Modell mit multitemporaler Fernerkundung (Landsat und Sentinel-2, 2011–2025) und partizipativer Citizen Science angewandt und Landschaftsmetriken (Patch-Dichte, Shannon-Diversitätsindex, Nettoprimärproduktion) wurden zusammen mit demografischen und infrastrukturellen Ebenen abgeleitet, um Belastungen zu bewerten. Quantitative Daten wurden mit Fokusgruppendiskussionen und partizipativer Kartierung erhoben. Die Ergebnisse zeigen, dass hohe Bevölkerungsdichten (bis zu 13.000 Personen/km²) und die Ausweitung von Ackerland (von 78 % auf 85 % zwischen 2011 und 2025) die primären Treiber der Degradation sind, die sich in Landschaftsfragmentierung und abnehmender Vegetationsproduktivität insbesondere in den östlichen Auenbereichen des LTBR äußern. Die Verknüpfung räumlicher Analysen mit lokalem Wissen macht eine räumlich differenzierte Vulnerabilität der Feuchtgebiete sichtbar, die durch demografische, landwirtschaftliche und klimatische Faktoren geprägt ist. Dieser Ansatz zeigt die Machbarkeit der Verschmelzung objektiver räumlicher Daten mit partizipativ erhobenen Evidenzen und bietet ein skalierbares Modell für evidenzbasierte Naturschutzpolitik im LTBR und in anderen empfindlichen Feuchtgebietssystemen.

INTRODUCTION

Wetlands are among the most biodiverse and valuable ecosystems, providing water purification, groundwater recharge, flood control, habitat for endangered species, and socio-economic benefits. Despite their importance, they face rapid degradation worldwide due to anthropogenic pressures like population growth, land-use conversion, and lack of monitoring [1].

UNESCO Biosphere Reserves are designed as pockets of hope for local solutions to global challenges [2]. The Lake Tana Biosphere Reserve (LTBR), designated in 2015, lies within the Eastern Afromontane Biodiversity Hotspot and contains Ethiopia's largest lake. Lake Tana is the source of the Blue Nile and hosts ecologically critical wetlands [3]. However, these wetlands face invasion by water hyacinth (*Eichhornia crassipes*), sedimentation, land-use changes, and a cultural perception of wetlands as "wastelands" that drives drainage for agriculture. Weak institutional monitoring and limited community engagement compound the problem.

To bridge policy and ecological realities, the *ComWet* project (funded by Africa UniNet project number P-144 Ethiopia) develops a participatory wetland health assessment, building on the prior *CoMon* project and aligning with Ramsar conservation goals, Ethiopian EPA regulations, and SDGs 13, 14, and 15. *ComWet* integrates citizen science approaches of focus groups, community mapping, and expert interviews with advanced geospatial technology. The current report applies an adapted Pressure-State-Response (PSR) framework (derived from the DPSIR model that also includes Drivers and Impacts) to assess LTBR wetland health. The PSR framework links socio-economic drivers (Pressures) to ecological changes (State) and management actions (Response), creating a clear cause-and-effect narrative. By synthesizing multi-temporal remote sensing with participatory data, this study aims to provide actionable evidence for LTBR management and long-term ecological monitoring.

METHODS

Description of the study area

The LTBR is located in northwestern Ethiopia (11°25'07"N–12°29'18"N, 36°54'01"E–37°47'20"E) (Figure 1), covering 695,885 ha. The size of the core area measures 22,841 ha (7,699 ha terrestrial); buffer area measures 187,567 ha (30,969 ha terrestrial); and transition area measures 485,477 ha (354,297 ha terrestrial). The region hosts some of the largest and most ecologically significant wetlands in Ethiopia and the Horn of Africa, along with important fish resources (67+ species, 70% endemic). Designated by UNESCO in June 2015, the LTBR contains Lake Tana, Ethiopia's largest highland freshwater lake and the main source of the Blue Nile, providing critical ecosystem services. It lies within the Eastern Afromontane Biodiversity Hotspot and includes four terrestrial and three freshwater Key

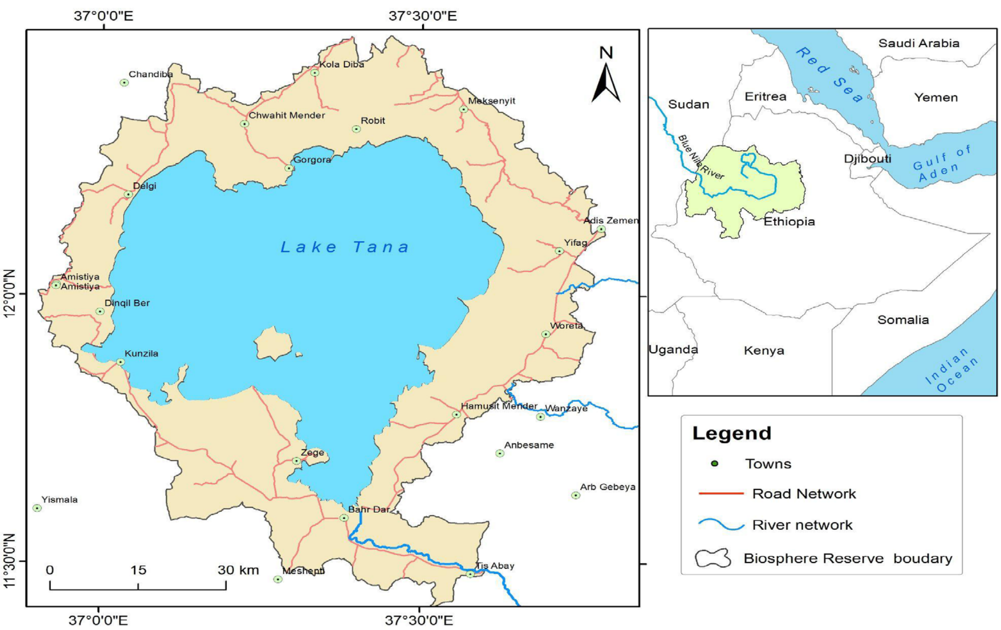

Fig. 1

Figure 1:
Map of the ComWet project area. (Source: ComWet project)

Abbildung 1:
Karte des ComWetProjektgebiets. (Quelle: Projekt ComWet)

Biodiversity Areas. It is recognized as an Important Bird Area and is of global significance for agricultural genetic diversity. Culturally, the reserve preserves unique Ethiopian Orthodox Tewahedo Church monasteries and churches, some dating to the 13th century, containing valuable Christian treasures [4].

Dataset type and sources

A comprehensive dataset array was compiled for wetland health assessment. Socioeconomic data (population density, urbanization) came from the national census [5]. Road network data from *OpenStreetMap*, verified by local records, assessed infrastructure impacts (fragmentation, areal shrinkage, pollution, biodiversity loss) [6]. Core spatial analysis used multitemporal Landsat and Sentinel2 imagery from USGS Earth Explorer [7] and Copernicus Data Space [8]. Landscape metrics were calculated using LecoS (QGIS) and FRAGSTATS [9], [10], including:

- **Patch Density (PD):** *patches per unit area; high values indicate fragmentation reducing habitat quality.*
- **Patch Richness (PR):** *diversity of patch types;* high values signal fragmentation.
- **Shannon Diversity Index (SHDI):** *diversity based on number and abundance of land cover types.*
- **Contagion Index:** *patch aggregation; high values* show contiguous stable wetlands; low values show scattered patches disrupting ecological processes.
- **Largest Patch Index (LPI):** *proportional size of dominant wetland patch;* low values signal habitat loss.

DATA ANALYSIS

To assess State and Pressures under the PSR model, we used Landsat series (5 TM, 8 OLI/TIRS, 9 OLI2) across three periods: pre-2015 (baseline), post-2015, and 2025. All images underwent radiometric calibration, atmospheric correction, and registration. Supervised classification, spectral indices (e.g., normalized difference vegetation index, NDVI), and land use-land cover (LULC) change analysis identified wetland loss, fragmentation, and hydrological alteration, with GPS field observations for groundtruthing.

To contextualize remote sensing and address PSR, a citizen science approach integrated local and institutional knowledge [11]. Methods included focus group discussions (FGDs) with community representatives, participatory community mapping (boundaries, degradation hotspots), and semistructured interviews with experts and local knowledge holders. This participatory layer grounds the research in local reality, validates spatial analysis, and strengthens proposed management responses.

By employing the PSR framework, remote sensing and participatory methods were iteratively integrated. Remote sensing provided spatiotemporal evidence of pressures, state, and responses; participatory methods explained underlying drivers, validated changes, elaborated impacts, and identified responses. The PSR framework synthesized these into a cause-and-effect narrative. Analysis combined quantitative (statistical analysis of remote sensing data) and qualitative (thematic analysis of FGD/interview transcripts) techniques, with triangulation, strengthening findings.

Tab. 1

Criteria	Indicator	Description	Data Source
Pressure	Population density	Inhabitants per km^2	[5]
	Cultivated area	Percentage of cultivated area per unit area	[7], [8]
	Proximity to road	Distance from road	[6]
	Urbanization rate	Percentage of urban population per unit area	Central Statistical Agency (CSA) & Land Use Land Cover (LULC)
State	PR	Number of patches	[7], [8]
	NPP	Net Primary Productivity	
	Average annual rainfall	Mean rainfall	Station data (Ethiopian Meteorological Institute, EMI)
	PD	Wetland area is divided by the provincial area	[8], [9]
	LPI	Largest patch area divided by total landscape area	
	SHDI	Proportion of patch type with in province area	
	Water quality	Water quality tests	In situ measurement
	Slope (°)	Angle of terrain (°)	[7]
Response	Wetland degradation rate	Percentage of wetland area loss within the province area	[7], [8]
	ESV	Ecosystem service value in US$ per ha per year	[7], [8]

Table 1: *Identified indicators and their description and source for wetland ecosystem health assessment.*

Tabelle 1: *Identifizierte Indikatoren sowie deren Beschreibung und Quellen für die Bewertung der Gesundheit von Feuchtgebiets-Ökosystemen*

RESULTS & DISCUSSION

This study systematically identified and computed a set of indicators capturing the complex interactions between human pressures, ecological states, and management responses affecting wetland health in LTBR. Integrating remote sensing metrics with participatory insights from local communities provides a comprehensive picture of how pressures translate into ecological change, enabling targeted conservation strategies.

Following the PSR framework, pressure indicators represent human activities that stress the environment (Figure 2) [12]. In the LTBR, population density ranges from 0 to 13,000 inhabitants per km^2, with highest concentrations in Fogera, Libo Kemkem, Dembia, Gondar Zuria, and Bahir Dar. These dense areas intensify wetland conversion to agriculture, settlements, and infrastructure, a trend confirmed by previous studies linking flood recession agriculture and settlement expansion to degradation [13], [14]. Cultivated land dominates the reserve, and its expansion into wetlands alters hydrology, reduces vegetation, and increases nutrient runoff. Fertile floodplains like Fogera are more than 75% cultivated [1], [14], fragmenting wetlands and reducing their buffering capacity. Citizen mapping further validates these trends, revealing annual dry season drainage campaigns led by development agents, reflecting the local perception of wetlands as “wastelands.” Globally, wetland conversion to agriculture is recognized as a leading cause of degradation [15]. Infrastructure development adds another pressure layer: road networks intersect wetland clusters in Fogera, Bahir Dar, and Bahir Dar Zuria, creating fragmentation, pollution, and hydrological disruption that facilitate settlement expansion

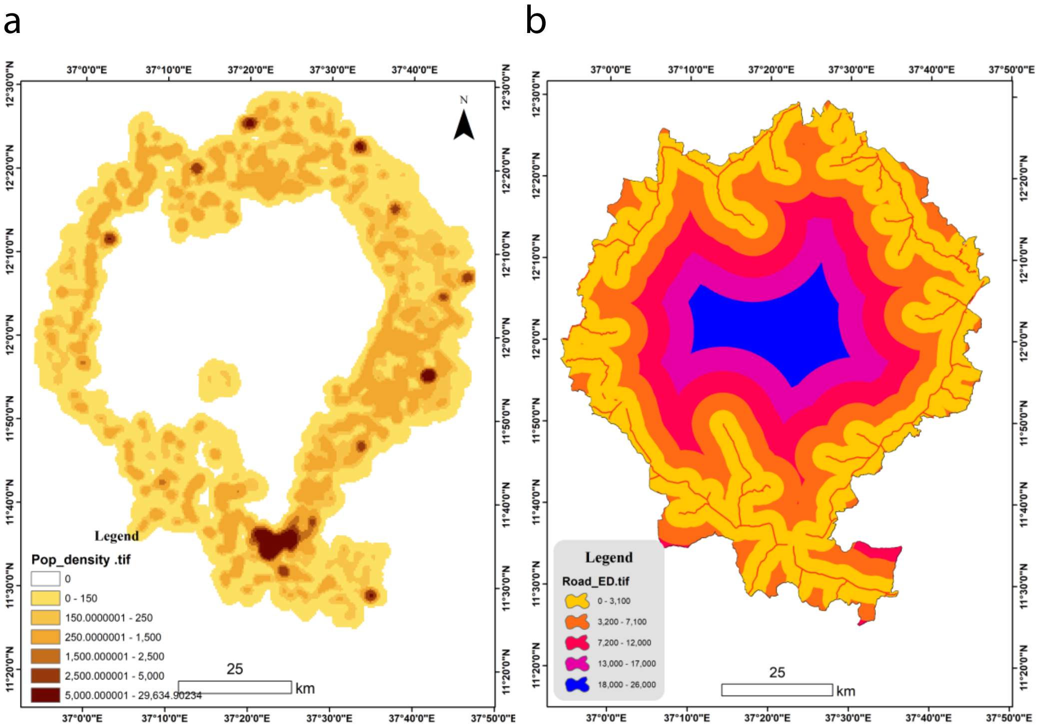

Fig. 2

Figure 2:
Population density (a), Road network (b). (Source: ComWet project)

Abbildung 2:
Bevölkerungsdichte (a), Straßennetz (b). (Quelle: Projekt ComWet)

and land conversion [16]. Urban expansion around Bahir Dar and other settlements has also accelerated, reflecting how socioeconomic development trajectories intersect with ecological vulnerability.

State indicators describe environmental conditions changed by pressure impacts (Figure 3) [12], [17]. Net Primary Productivity (NPP), derived from NDVI, is a key measure of ecosystem function [18], [19]. Most of the LTBR exhibits low productivity (<5 g/m²), while approximately 667 km² experience moderate productivity (10–20 g/m²); areas with high productivity (>20 g/m²) are negligible. Moderate NPP values are concentrated in the eastern floodplain, northern Dembia, North Achefer along the Gilgel Abbay, and smaller pockets in Bahir Dar Zuria, corresponding to intensified cultivation and settlement expansion. Widespread low values signal reduced vegetation resilience and potential degradation. Rainfall distribution, derived from over 25 years of meteorological records, shows a mean annual range of 850–1500 mm. Southern districts including Dera, Bahir Dar Zuria, Dangla, and Alefa receive relatively higher rainfall, while most of the reserve experiences totals below 1200 mm. Wetter zones sustain hydrological connectivity but risk flooding, sediment deposition, and nutrient loading; rainfall-deficient areas face water shortages, reduced soil moisture, and wetland contraction. When coupled with population pressure and agricultural expansion, rainfall variability intensifies ecological stress [17], [20].

Landscape fragmentation metrics further illustrate ecosystem state: PD covers ~270 km² (including protected and church forests), with high values indicating fragmentation and edge effects [21]. PR and landscape diversity indices reveal increasing cropland and settlement patches. Water quality, another state indicator, declines near settlements and cultivated areas due to nutrient loading, turbidity, and eutrophication [22]. Together, these state indicators demonstrate that LTBR wetlands are characterized by low vegetation productivity, uneven rainfall distribution, increasing fragmentation, declining water quality, and terraindriven vulnerability, directly linking socioeconomic drivers to physical and biological degradation.

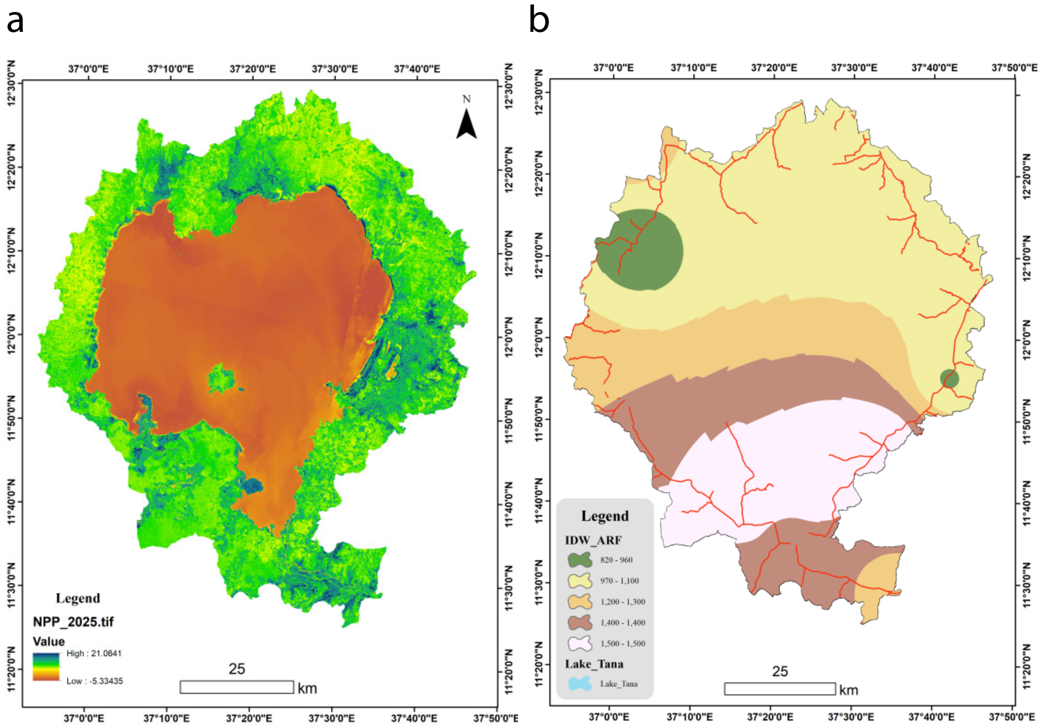

Fig. 3

Figure 3: Net Primary Productivity (NPP) in 2025 (a); Annual rainfall distribution in the LTBR area (b). (Source: ComWet project)

Abbildung 3: *Nettoprimärproduktion (NPP) im Jahr 2025 (a); jährliche Niederschlagsverteilung im LTBRGebiet (b). (Quelle: Projekt ComWet)*

Response indicators in this study reflect the manifested consequences of pressures and states, expressed as degree of wetland degradation and loss of ecosystem service values [12], [23]. In the LTBR, wetlands are distributed unevenly, with the majority concentrated in the eastern Fogera floodplain (Fogera and LiboKemkem districts), additional clusters in the south and southwest along the Gilgel Abbay River in Achefer District, and in the north along the Megech River in Dembia District (Figure 4) [13], [24]. The eastern floodplain features high population density and moderate NPP, reflecting intensive cultivation and settlement expansion. These spatial contrasts illustrate that wetland degradation is not uniform but context-specific, driven by the interaction of climatic variability and human activity. As wetlands fragment and lose ecological integrity, their capacity to provide

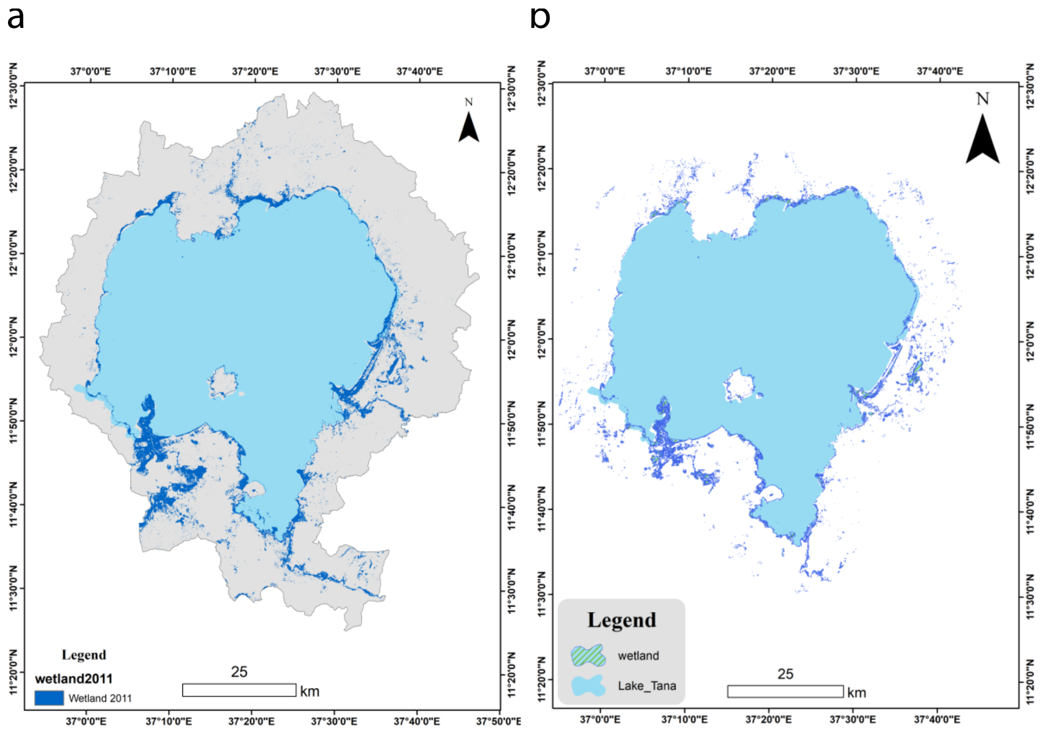

Fig. 4

Figure 4: Wetland distribution derived from the Landsat imagery In 2011 (a); in 2025 (b). (Source: ComWet project)

Abbildung 4: *Verteilung der Feuchtgebiete, abgeleitet aus LandsatBilddaten, 2011 (a); 2025 (b). (Quelle: Projekt Com Wet)* ecosystem services—including water flow regulation, biodiversity support, fisheries, grazing land, and flood buffering—declines, undermining both ecological sustainability and local livelihoods.

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