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Recent mechanisms of surface ecological changes driven by climate change and human activities in Lake Biwa, Japan

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Lake Biwa, Japan represents a crucial example of the complex climatic and anthropogenic drivers influencing lake ecological transformations, vital to informing Sustainable Development Goals globally. This study utilizes 2002–2022 Landsat, MODIS and *in situ* Lake Biwa monitoring data to analyze surface layer spatiotemporal dynamics across interrelated vegetation, water quality and meteorological indicators—encompassing Normalized Difference Vegetation Index (NDVI), nitrogen (N), phosphorus (P), chlorophyll-a (Chl) and water temperature (W-TEM). Upward NDVI raster trends were found over 20 years alongside prevalent N, P and Chl declines—although some increases did occur spatially in P and Chl—while W-TEM mostly rose lakewide. Southwest–northeast gradients typified distributions. Further attribution analyses revealed W-TEM as the primary N, P and Chl driver, while agricultural expansion and urbanization mediated crucial N and P changes. Moreover, wind speed (WS), Crop, W-TEM, minimum temperature (TMMN), Chl and N constituted top NDVI raster influence factors respectively. These novel integrated models quantifying Lake Biwa ecological responses to multifaceted environmental change provide new perspectives to inform sustainable management of Lake Biwa itself and critical freshwater resources worldwide.

KEYWORDS

climate change, chlorophyll, human activities, Lake Biwa, NDVI, nitrogen, phosphorus

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Abbreviations: AET, actual evapotranspiration; Chl, chlorophyll-a; City, area of cities; Crop, area of cropland; MODIS, Moderate-resolution Imaging Spectroradiometer; N, nitrogen; NDVI, Normalized Difference Vegetation Index; P, phosphorus; PLSR, partial least squares regression; RS, remote sensing; SDGs, Global Sustainable Development Goals; SRAD, surface shortwave radiation; TMMN, minimum temperature; TMMX, maximum temperature; VPD, vapor pressure difference; WS, wind speed at 10 meters; W-TEM, water temperature.

1 Introduction

Global climate change alongside rising human population growth and associated agricultural expansion, industrialization and urbanization have profoundly impacted lake and river ecosystems by altering hydrological balances and threatening critical water resources and ecological health (Ishtiaque et al., 2022; Jeppesen et al., 2014; Salk et al., 2022). As integrally interconnected carbon sinks and sources, shifts in lake ecology additionally drive wider carbon cycling changes (Meyers, 1997). Japan's Lake Biwa represents an archetypal example of a lake ecosystem undergoing rapid transformations due to multifaceted human and climatic pressures (Xue et al., 2021). As an invaluable regional water resource and ecosystem underpinning key economic, ecological and societal services, Lake Biwa possesses immense significance. However, while its ecological disturbances mirror wider global lake trends, Lake Biwa further exhibits unique geographical and ecological characteristics molding localized responses (Kumagai, 2008; Le Moal et al., 2019). Therefore, this study seeks to deeply analyze Lake Biwa's complex ecological transitions under interacting human and climatic influences through an interconnected surface layer indicator framework, in order to inform sustainable regional resource management pathways supporting global climate change mitigation efforts and Sustainable Development Goals.

Lake Biwa's shifting ecology depends upon climatic, hydrological and environmental change drivers. Recent climate shifts combined with agricultural and urban encroachment have altered nutrient balances and water quality regimes (Reichwaldt and Ghadouani, 2012; Zhu et al., 2015; Zhou et al., 2022). Anthropogenic disruptions of nitrogen, phosphorus and water quality relationships cascade to impact vegetation dynamics and ecosystem functioning (Zhu et al., 2015; Xu et al., 2020; Lemenkova, 2022). Global population growth and intensifying urbanization since 1900 has amplified nutrient loads across watersheds worldwide (Bennett et al., 2001; Le Moal et al., 2019), evidenced in heavily populated regions including China's eutrophic Lake Taihu (Zhang et al., 2016). Satellite sensors now provide unparalleled spatiotemporal visibility into global lake processes including water quality, algal blooms and carbon cycling to inform conservation priorities (Jarvie et al., 2018; Huo et al., 2021; Saravanan et al., 2021; Wu et al., 2023a). While Lake Biwa historically experienced 1990s–2000s eutrophication pressures, subsequent water quality and ecological improvements have occurred regionally (Nakamura, 2002; Nishino, 2012). Further research should now disentangle complex anthropogenic impact mechanisms affecting contemporary Lake Biwa amid continued environmental change.

Hydrological monitoring lends critical ecological insights through water levels, aquatic vegetation mapped via Normalized Difference Vegetation Indices (NDVIs), and phytoplankton abundances—key ecological health indicators (Kiage and Walker, 2009; Qing et al., 2020). Regional nitrogen, phosphorus, chlorophyll-a and water temperature profiles similarly inform surface layer health assessments (Dodds et al., 1998; Takamura et al., 2003; Filstrup and Downing, 2017; Liang et al., 2020). Prior Lake Biwa research has quantified hydrological cycle interdependencies with regional seismicity and climatic factors using integrated *in situ* gauge and satellite data (Xue et al., 2021). Relative nitrogen versus phosphorus controls over eutrophication also relate directly to depth and water quality regimes (Qin et al., 2020). Climate change driven regional warming trends further impact ecological functioning through lake temperature influences (Yamashiki et al., 2010; Nazari-Sharabian et al., 2018). Cascading temperature effects on stratification, nutrient cycling and phytoplankton productivity provide important mechanistic links to eutrophication (Elliott and Defew, 2012; Bhagowati and Ahamad, 2019; Salk et al., 2022). Thus, coordinated hydrological monitoring offers comprehensive eutrophication insights.

Meteorological shifts driven by climate change have also been observed across actual evapotranspiration, radiation, vapor pressure, air temperatures and wind patterns over Lake Biwa with ecological implications (Shao et al., 2015; Du et al., 2018; Zhou et al., 2022). Process-based models successfully reproduce Lake Biwa ecosystem responses to observed climate factor changes from 1955 to 2005 (Lemenkova, 2022; Zhou et al., 2022). These analyses clearly demonstrate meteorology linkages to ecological transformations, informing sustainable management needs under non-stationary climate change.

While previous research has generated critical insights about drivers of lake environmental change, recent studies underscore key knowledge gaps regarding multifaceted anthropogenic impacts on Lake Biwa across space and time in the context of climate change. This research encompasses an expansive set of interconnected parameters—spanning NVDI, water quality indicators (nitrogen, phosphorus, chlorophyll-a, temperature), meteorological variables (evapotranspiration, radiation, vapor pressure deficit, air temperature)—to unveil novel perspectives into relationships between regional meteorology and ecological transformations. This integrated assessment approach enables an improved theoretical framework for formulating adaptive management strategies responsive to intensifying environmental change pressures. Study outcomes are further intended to provide valuable references for promoting ecological sustainability and resilience of Lake Biwa and other comparable freshwater ecosystems moving forward.

This comprehensive 2002–2022 Lake Biwa assessment incorporating Landsat, MODIS and hydrological data offers unprecedented visibility into multidimensional ecological changes. The integrated framework assessing connections across NDVI, water quality indicators, meteorology and human pressures provides new perspectives for elucidating climate change and anthropogenic impacts on Lake Biwa. Study findings further offer scientifically grounded guidance to promote sustainable regional environmental management aligned with global priorities.

2 Materials and methods

2.1 Study area

Japan's largest freshwater ecosystem, the over 4-million-year-old Lake Biwa spans 670 square kilometers in Shiga Prefecture.

Containing 27.5 billion cubic meters of water, Lake Biwa has sufficient capacity to meet the entire Yodo River basin population's 11-year water demands. As a vital supply for 14.5 million downstream residents in Kyoto, Osaka and Hyogo via the Seta and Yodo tributaries, the lake underpins regional water security, economies, and sustainable development (Kumagai et al., 2003; Kawanabe et al., 2020). A biodiversity refuge with over 60 endemic species, ongoing environmental change threatens Lake Biwa's ecological character and services.

Spatiotemporal 2002–2022 hydrological data from 17 Lake Biwa water monitoring stations (Figure 1) enables quantitative analysis of ecological transitions across this critical supply amidst intensifying climatic and human pressures on the lake and dependent communities. High-frequency water quality indicators were obtained from long-term Shiga Prefecture Lake Biwa Environmental Research Institute programs for 11 northern sites, 5 southern sites and 1 Seta River site, enabling pollution and eutrophication trend assessments via nitrogen, phosphorus, chlorophyll-a, and water temperature.

2.2 Data

2.2.1 Measured data

Lake Biwa Environmental Research Institute long-term monitoring (https://www.lberi.jp/investigate/long_term) provided 2002–2022 water quality and ecosystem health indicator data for 11 northern sites, 5 southern sites and 1 Seta River site at 0.5 m water depth (Figure 1). Incorporating nitrogen, phosphorus, chlorophyll-a and water temperature measurements, this extensive spatiotemporal sampling enables quantification of pollution, eutrophication and ecological variation trends across Lake Biwa.

2.2.2 Vegetation data

Landsat 5, 8 and 9 satellite 30 m resolution top-of-atmosphere reflectance data was extracted via Google Earth Engine (developers.google.com/earth-engine) to derive annual maximum value composites and per-pixel monthly NDVI time series from 2002–2022 across the study area (Table 1). This enables vegetation change

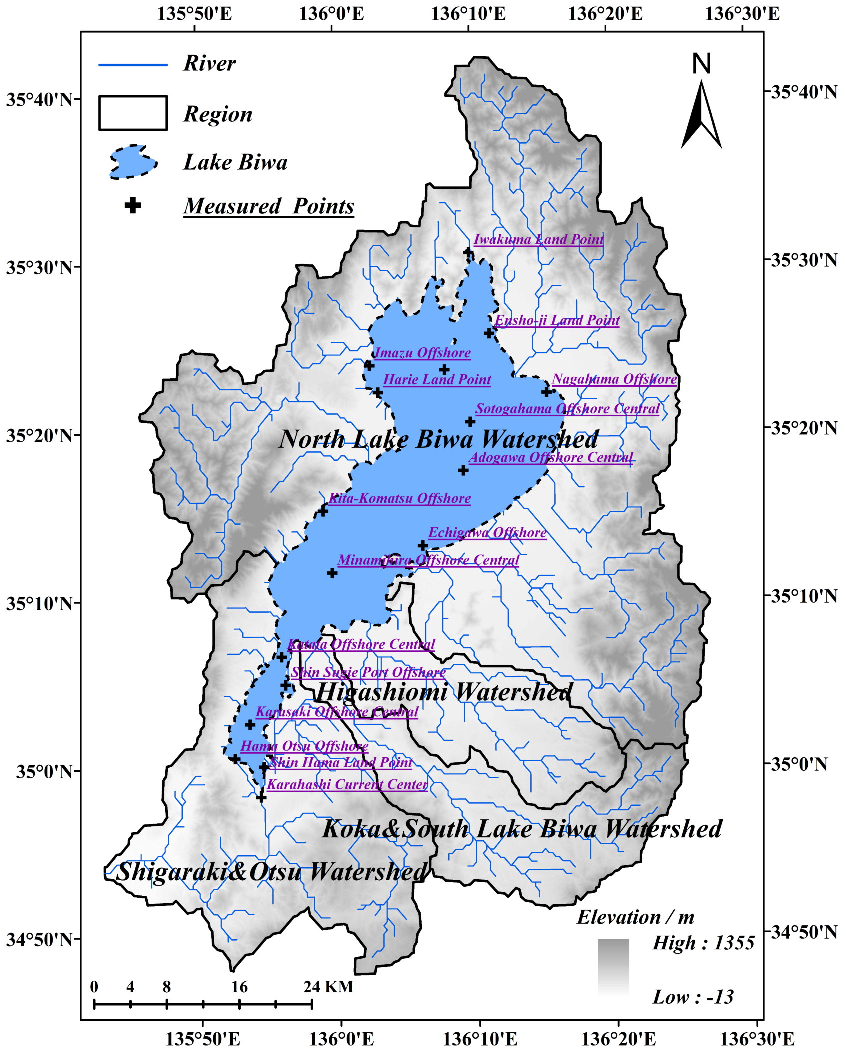

FIGURE 1
Study area.

detection across Lake Biwa through the decades-long Landsat record.

2.2.3 Climate data

Gridded monthly TerraClimate climate data (Abatzoglou et al., 2018) was utilized in this study for the Lake Biwa region from 2002 to 2022. TerraClimate integrates high-resolution climatological normals from WorldClim with time-varying data from CRU Ts4.0 and Japanese 55-year Reanalysis (JRA55) (Table 1). This enabled correlation analysis between regional meteorology and Lake Biwa ecology.

2.2.4 Supporting data

The 30-meter resolution digital elevation information from the NASA Shuttle Radar Topography Mission (Farr et al., 2007) provided terrain perspectives (Table 1) enabling analysis of topographic influences on spatial ecological gradients. Crop and City is the land area selected from the study area overview map (Figure 1), utilizing the area of Cropland and Cities from the IGBP classification of MODIS MCD12Q1 for 2002–2022 (Justice et al., 2002).

2.3 Methods

2.3.1 Calculation of normalized difference vegetation index

NDVI can be extracted by subtracting the ratio of a red band and near-infrared band plus a red band from the near-infrared band of the image.

$$NDVI = \frac{NIR - R}{NIR + R} \quad (1)$$

Where: NIR represents the reflectance in the near-infrared band. R represents the reflectance in the visible red band. The $NDVI$ values range from −1 to 1. Negative values typically correspond to water, values close to zero may indicate bare soil or very low vegetation cover, and positive values indicate vegetation, with higher values signifying denser vegetation.

2.3.2 Partial least squares regression

Partial least squares regression (PLSR) enables analysis of multivariate relationships in contexts with more predictor variables than observations and potential inter-variable multicollinearities (Geladi and Kowalski, 1986). This study leverages PLSR to construct empirical models quantifying connections between climatic factors and Lake Biwa vegetation area changes, selecting from nine candidates (evapotranspiration, radiation, vapor pressure deficit, wind speed, maximum temperature, minimum temperature, water temperature, crop area, city area). Careful tuning of the PLSR principal component parameter is critical to balance model accuracy with overfitting avoidance for valid analytics. By iteratively evaluating out-of-sample PLSR cross-validation root mean square errors across different principal component choices for each vegetation–climate pair, optimal selections with minimized validation errors can be identified, enhancing model reliability (Ma et al., 2023). The systematic procedure provides robust vegetation–climate models from the multivariate, collinear Lake Biwa dataset.

TABLE 1 Remote sensing and reanalysis data products.

Product	Type	Temporal resolution	Spatial resolution	URL source
Landsat 5	Top-of-atmosphere (TOA) reflectance	2002.01~ 2011.11	30 m	https://landsat.gsfc.nasa.gov/data/landsat-5/ [Accessed on 2 August 2023]
Landsat 8	Top-of-atmosphere (TOA) reflectance	2013.11~ 2021.12	30 m	https://landsat.gsfc.nasa.gov/data/landsat-8/ [Accessed on 2 August 2023]
Landsat 9	Top-of-atmosphere (TOA) reflectance	2022.01~ 2023.01	30 m	https://landsat.gsfc.nasa.gov/data/landsat-9/ [Accessed on 2 August 2023]
SRTM	Digital Elevation Model (DEM)	—	30 m	https://www.usgs.gov/ [Accessed on 5 June 2023]
MCD12Q1	Landcover (IGBP)	Yearly	500 m	https://modis.gsfc.nasa.gov/ [Accessed on 2 July 2023]
TerraClimate	Actual evapotranspiration (AET)	Monthly	1/24°~4 km	https://www.ecmwf.int [Accessed on 8 May 2023]
TerraClimate	Surface shortwave radiation (SRAD)	Monthly	1/24°~4 km	https://www.ecmwf.int [Accessed on 8 May 2023]
TerraClimate	Vapor pressure difference (VPD)	Monthly	1/24°~4 km	https://www.ecmwf.int [Accessed on 8 May 2023]
TerraClimate	Maximum temperature (TMMX)	Monthly	1/24°~4 km	https://www.ecmwf.int [Accessed on 8 May 2023]
TerraClimate	Minimum temperature (TMMN)	Monthly	1/24°~4 km	https://www.ecmwf.int [Accessed on 8 May 2023]
TerraClimate	Wind speed at 10m (VS)	Monthly	1/24°~4 km	https://www.ecmwf.int [Accessed on 8 May 2023]

3 Results

3.1 Vegetation changes of Lake Biwa

Analysis of annual 2002–2022 NDVI pixels across Lake Biwa (excluding 2012) indicates uptrending vegetation over the past two decades. Categorizing pixels by NDVI thresholds (0.2–0.3, 0.3–0.4, 0.4–1) revealed higher 0.2–0.3 fractions, indirectly reflecting heightened satellite-detected greenness and eutrophication levels. Years 2008, 2013–2015 and 2021–2022 marked peak periods, while 2003 and 2018–2019 represented lower NDVI years (Figure 2).

3.2 Spatiotemporal variation of nitrogen, phosphorus, chlorophyll-a, and water temperature

Distributions and ranges were also quantified across depth-profiled 2002–2022 nitrogen (0.229–0.445 mg/L), phosphorus (0.007–0.030 mg/L), chlorophyll-a (2.268–8.745 µg/L) and water temperatures (16.73–17.56°C) averaged across 17 Lake Biwa stations. Kriging interpolation (Figure 3) depicted southwest-northeast declines in all parameters, highlighting significant regional water temperature influence.

Long-term assessments further demonstrated declines at most sampling points for nitrogen and phosphorus over 20 years. However localized phosphorus and chlorophyll-a increases emerged, often concurrently with predominant water temperature rises. Chlorophyll-a exhibited substantial interannual variability without directional trends (Figure 4), yet some synchronization was visible with 2003–2006 and 2015–2017 co-elevated, versus 2006–2007 and 2013–2016 co-suppressed phases. Intra-annual analysis revealed winter/spring nitrogen and chlorophyll peaks, contrasting with heights in summer water temperatures (Figure 5). These intricate spatiotemporal patterns underscore complex interdependent processes regulating Lake Biwa water quality.

3.3 Attribution of nitrogen, phosphorus, chlorophyll-a, and NDVI raster changes

Attribution assessments quantified relative contributions of regional meteorology, temperature, land use changes and human activities toward 2002–2022 fluctuations in Lake Biwa water quality and vegetation indices. Considering nitrogen dynamics, dominant factors included water temperature (43.3%), urban expansion (36.5%), vapor pressure deficit (10.6%), wind speed (7.0%) and maximum air temperatures (4.7%). Phosphorus variations were largely attributable to water temperature (40.1%), urban (37.6%) and agricultural land use changes (24.9%), alongside evapotranspiration (26.7%), radiation (19.1%) and maximum temperatures (21.2%). Water temperature (79.3%) also overwhelmingly explained chlorophyll-a shifts, followed by evapotranspiration (67.3%), radiation (44.4%) and vapor pressure deficit (42.4%). Finally, wind speed (55.5%), crops (34.3%), water temperature (33.3%), minimum air temperature (67.3%), chlorophyll-a (28.6%) and nitrogen (23.5%) constituted primary drivers of detected uptrends in Lake Biwa vegetative index raster counts (Figure 6).

4 Discussion

4.1 Changes in the vegetation index of Lake Biwa

Uptrending 2002–2022 Lake Biwa NDVI rasters suggest intensification of regional human activities and global climate change vegetation impacts. Hsieh et al. (2010) found 1960s–1990s oligotrophic conditions from management intervention shifted post 1990s warming enabling vegetation expansion, though overall ecological health persists (Flaim et al., 2016).

Global analyses reveal combined climatic and anthropogenic NDVI drivers, including intensified agriculture expanding Iran's Lake Urmia vegetation (Tootoonchi et al., 2020) while Yangtze River basin shifts were 79.29% attributable to human activities versus 20.71% climate change (Yi et al., 2022). Analogously, Lake

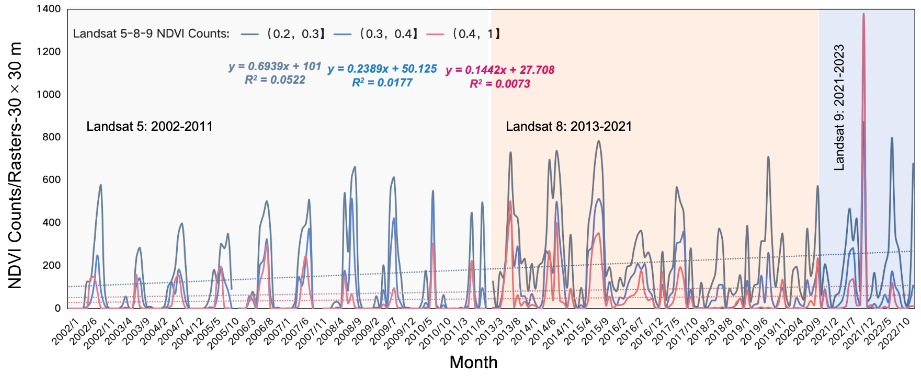

FIGURE 2
Monthly scale raster counts based on Landsat band NDVI and based on numerical values.

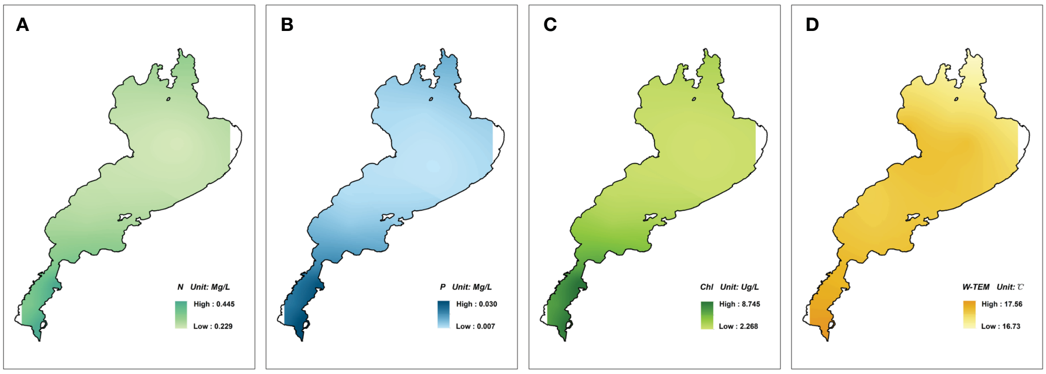

FIGURE 3
Spatial distribution of yearly mean (calculated by kriging difference from 17 sample points) indicators of **(A)** nitrogen, **(B)** phosphorus, **(C)** chlorophyll-a, and **(D)** water temperature from 2002 to 2022 in Lake Biwa.

Biwa has undergone complex eutrophication–oligotrophication transitions from intersecting nutrient, climatic and management feedbacks. Despite ubiquitous climate NDVI linkages, local human pressures remain equally influential.

4.2 Changes in nitrogen and phosphorus indicators in Lake Biwa

As nitrogen–phosphorus ratios strongly dictate algal development and lake ecosystem responses to nutrient perturbation, observed southwest–northeast gradients in Lake Biwa nitrogen, phosphorus, chlorophyll-a and temperature highlight southern zones facing enhanced eutrophication threats due to positional nutrient loading disparities.

Long-term nitrogen and phosphorus declines at most sampling sites imply agricultural and sewage treatment improvements (Nakanishi et al., 2022), however continued uncontrolled phosphorus inputs may sustain eutrophication risks (Nakakuni et al., 2022). Concurrent warming from global climate change appears to drive thermal structure shifts enabling summer algal proliferation (Yan et al., 2022). Dynamic chlorophyll-a lacking trends indicates seasonal and inlet–outlet biomass regulation (Liu et al., 2023; Wu et al., 2023b). Interactive shifts in nutrient availability and temperature differentially benefit specific phytoplankton groups (Shatwell and Köhler, 2019; Wurtsbaugh et al., 2019; Qin et al., 2020), highlighting nitrogen-phosphorus ratios as key indicators of lake transformations.

4.3 Attribution of ecological changes in Lake Biwa

This study revealed wind speed, agricultural extent, lake water temperature, air minimum temperature, chlorophyll-a and nitrogen as dominant factors driving detected uptrends in Lake Biwa NDVI raster area from 2002–2022. Furthermore, rising water temperatures most profoundly impacted observed nitrogen, phosphorus and chlorophyll-a shifts, while urban expansion was found to strongly influence detected nitrogen and phosphorus dynamics.

A variety of factors, including WS, Crop, W-TEM, TMMN, Chl and nitrogen levels, collectively influence the changes in NDVI raster area. Increased wind speed, especially during precipitation events, can cause changes in Chl concentration in coastal areas, thereby affecting NDVI values (Valentin et al., 2021). Climate change also impacts vegetation NDVI by altering air and water temperatures, with vegetation greenness variability primarily driven by climate, and vegetation of different land use types being sensitive to climate change (Revadekar et al., 2012; Bao et al., 2021). NDVI also responds differently to seasonal changes in temperature and precipitation patterns (Yan et al., 2022). Furthermore, studies indicate that nitrogen levels in lakes and oceans affect NDVI by influencing the growth of plants and algae, with the impact dependent on the supply, form, ratio, and environmental conditions of nitrogen (Nizzoli et al., 2018; Palacin-Lizarbe et al., 2020). The balance of nitrogen and phosphorus is crucial in managing eutrophication in aquatic ecosystems and maintaining clear water bodies. Therefore, changes in lake NDVI are the result of the interaction between climate and human activities.

W-TEM affects the levels of nitrogen, phosphorus, and Chl in aquatic ecosystems through various mechanisms. Research indicates that water temperature not only directly influences the growth rates of algae and aquatic plants but also indirectly alters nutrient cycling and ecosystem dynamics (Beisner et al., 2003; Zhang et al., 2020). Liang et al. suggest that under the backdrop of climate warming, elevated water temperatures can increase the prevalence of certain algae, especially when ample phosphorus nutrients are available, and may also change the patterns of nitrogen cycling in aquatic ecosystems (Liang et al., 2020). The impact of temperature on these ecosystem elements is complex and is influenced by a combination of ecosystem type, other environmental stresses, and local environmental characteristics (Zhang et al., 2020). Therefore, research assessing the impact of changes in W-TEM on lake nitrogen, phosphorus, and Chl is crucial to understand and predict ecosystem responses to climate change.

Changes in city area play a key role in the changes in nitrogen and phosphorus. Studies have shown that agricultural and

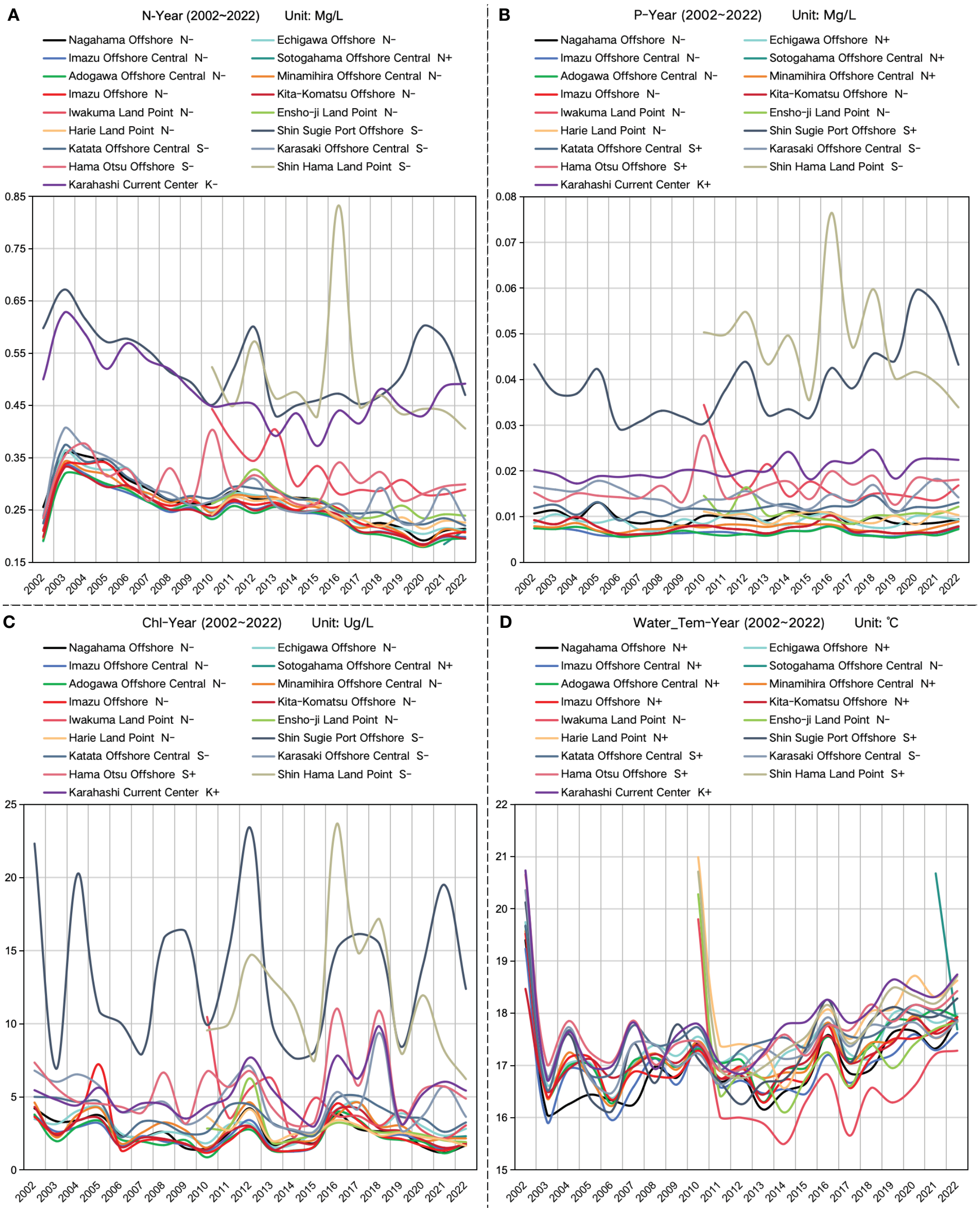

FIGURE 4
Time series of yearly mean indicators of **(A)** nitrogen, **(B)** phosphorus, **(C)** chlorophyll-a, and **(D)** water temperature from 2002 to 2022 in Lake Biwa. (N: Northern Lake, S: Southern Lake, K: Karahashi Current Center, +: Positive trend, −: Negative trend).

impervious city lands produce higher levels of nitrogen and phosphorus than other land surfaces, severely affecting water quality in water bodies (Tong and Chen, 2002). Research has also found that climate and land use changes have a significant inhibitory effect on water retention, nitrogen emissions, and phosphorus emissions (Bai et al., 2019). These factors act together on lake ecosystems and may have profound effects on biological networks, chemical cycles, and their overall health. Therefore, protecting water quality requires integrated management strategies that consider climate and land use changes.

4.4 Uncertainty analysis and prospects

This paper investigates the ecological changes of the surface layer of Lake Biwa and its driving factors through Landsat 5/8/9 and MODIS remote sensing data, measured data, and reanalyzed data. There are inconsistencies in the spatiotemporal accuracy of remote sensing data and its products, as well as inaccuracies in the representation of ground objects. For example, the saturation defect of NDVI may lead to a loss of resolution in areas with high vegetation coverage, while errors in measured data, such as

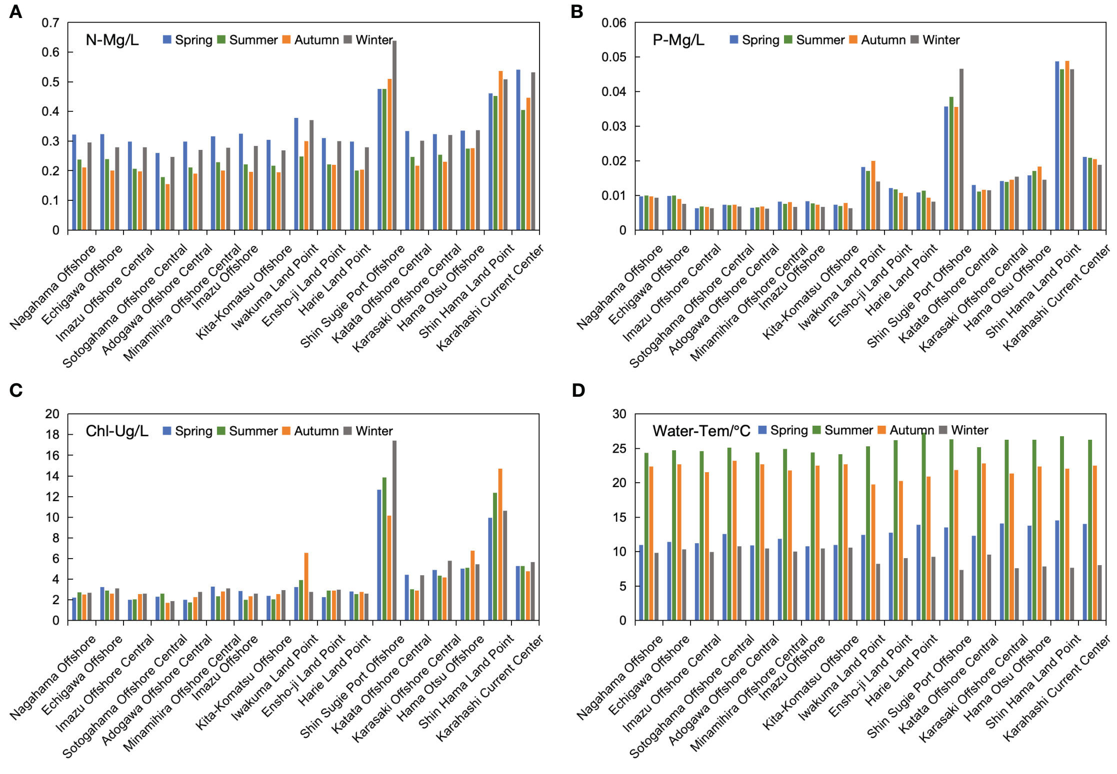

FIGURE 5
Seasonal changes of **(A)** nitrogen, **(B)** phosphorus, **(C)** chlorophyll-a, and **(D)** water temperature in Lake Biwa during 2002–2022.

improper sensor calibration, inaccurate atmospheric correction, or inappropriate selection of ground sampling points, can affect the accuracy of the data. Although the reanalyzed data has a long time series, it has the defect of low spatial accuracy, which may affect the accuracy of data in medium and small-scale regions. At the same time, errors in measured data are also a factor affecting the accuracy of the research, including but not limited to issues such as sensor calibration, inaccurate atmospheric correction, representativeness of ground sampling points, and irregularities in human operation. However, these shortcomings do not affect the scientific nature and accuracy of the article. The study compares remote sensing data with empirical data and conducts detailed assessments to ensure the scientific nature and reliability of the results.

To overcome these limitations and improve the accuracy of future research, future studies need to improve data calibration accuracy, increase measured samples, use advanced algorithms to reduce analysis uncertainty, and monitor ecological changes over a longer time span to establish a comprehensive ecological model to enhance the understanding and protection of the Lake Biwa ecosystem. These measures will help to improve the overall quality of the research and ensure the scientific nature and accuracy of the results, even in the face of uncertainties and challenges.

5 Conclusion

This study, based on the infrared and near-infrared bands of Landsat and MODIS land use remote sensing data products, as well as reanalyzed and measured data, analyzes the ecological changes of the surface layer of Lake Biwa in Japan. It calculates and analyzes the high-precision NDVI vegetation index and explores the changes in the number of rasters and the spatiotemporal variations of surface nitrogen, phosphorus, chlorophyll-a, and water temperature in the lake area. The study attributes the changes in nitrogen, phosphorus, and chlorophyll-a in the lake area to climatic factors such as AET, SRAD, VPD, WS, TMMX, TMMN, W-TEM, and human activities such as changes in crop and city area, and ultimately integrates these factors to attribute the changes in NDVI comprehensively. We found that:

1. From 2002 to 2022, the number of NDVI rasters in Lake Biwa showed an upward trend, with the trend weakening as the NDVI value range increased.
2. The spatial distribution pattern of nitrogen, phosphorus, chlorophyll-a, and water temperature decreased from the southwest to the northeast of Lake Biwa at 17 sample points from 2002 to 2022, with nitrogen, phosphorus and chlorophyll-a showing a downward trend at most sample points over the past 20 years, but increasing trends in phosphorus and chlorophyll at some sites and water temperature at most sites.
3. In terms of factor contribution rates, WS (55.5%), Crop (34.3%), W-TEM (33.3%), TMMN (67.3%), Chl (28.6%), and N (23.5%) had the greatest impact on the change in the number of NDVI rasters. Among them, water temperature (N: 43.4%, P: 40.1%, Chl: 79.3%) had the greatest impact on

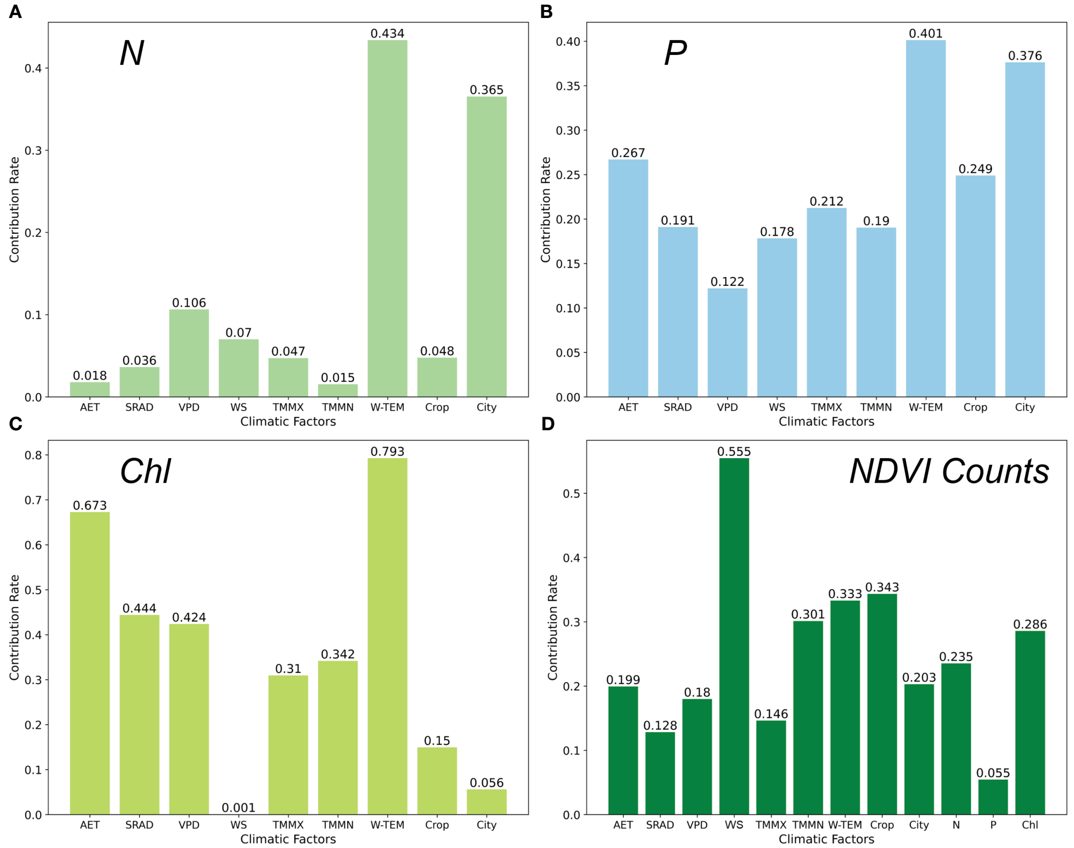

FIGURE 6
Contribution of climatic and anthropogenic factors to **(A)** nitrogen, **(B)** phosphorus, **(C)** chlorophyll-a, and **(D)** NDVI counts change in Lake Biwa.

the changes in nitrogen, phosphorus, and chlorophyll-a, followed by changes in city area (N: 36.5%, P: 37.6%) which played a key role in the changes in nitrogen and phosphorus.

This study provides new insights for the monitoring and application of ecological indicators in lakes or oceans, offers a scientific theoretical basis for the ecological protection management and decision-making of lakes or oceans, and contributes to the ecological and environmental protection and development of similar water bodies.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

BG: Conceptualization, Data curation, Formal Analysis, Software, Visualization, Writing – original draft. MC: Investigation, Methodology, Writing – review & editing. HH: Conceptualization, Data curation, Formal Analysis, Methodology, Software, Visualization, Writing – original draft. YY: Funding acquisition, Supervision, Writing – review & editing. KI: Funding acquisition, Supervision, Writing – review & editing. CJ: Resources, Writing – review & editing. JC: Funding acquisition, Supervision, Writing – review & editing. SI: Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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