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Long-Term Expansion, Ecosystem Services and Management Trade-Offs of *Phragmites karka* in Asia's Largest Lagoon

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ABSTRACT

Coastal lagoons are increasingly altered by hydrological modification and catchment-derived nutrient loading, driving shifts in macrophyte dominance and creating complex management trade-offs. In Chilika lagoon, India, the emergent macrophyte *Phragmites karka* has expanded, raising concerns about impacts on native macrophytes, habitat heterogeneity and biodiversity. We integrated Landsat imagery (1991–2025) with field measurements of water quality, sediment biogeochemistry, metal accumulation and population demography to evaluate its expansion implications. *P. karka* exhibited alternating phases of expansion and contraction, and occupied approximately 8611.21 ha in 2025. Established stands occurred under low-salinity, and reducing conditions, and contained sediment carbon and nitrogen stocks of $50.09 \pm 18.11 \text{ Mg C ha}^{-1}$ and $4.81 \pm 1.60 \text{ Mg N ha}^{-1}$, corresponding to approximately 0.43 million Mg C and 41,420 Mg N across the extent. Metals were below-detection limits in surface waters but accumulated in sediments and plant tissues, with biota-sediment accumulation factors > 1 for Mn, Ni and Co. Population demography indicated recruitment and positive growth, suggesting persistence under prevailing conditions. These findings document habitat-specific biogeochemical attributes, but do not imply that they outweigh biodiversity concerns, establish conservation equivalence with native habitats or alter the invasive status of *P. karka*. Management should remain site-specific: restoration, nutrient-source reduction, hydrological rehabilitation, containment and removal should be prioritized where native-community recovery is feasible or sensitive habitats are threatened. Monitored temporary retention may be considered only where restoration is constrained, risks to sensitive habitats and native communities are low and rapid removal could mobilize sediments, nutrients or contaminants. Decisions should remain conditional, reversible and periodically reassessed.

1 | Introduction

Coastal lagoons are among the most intensively managed social-ecological systems worldwide, providing fisheries, biodiversity support, water regulation and climate-mitigation services, while simultaneously receiving disproportionate anthropogenic pressures from catchments and coastal development (Pérez-Ruzafa et al. 2011; Piñeiro-Juncal et al. 2026). Over decadal timescales, these drivers can fundamentally alter ecological baselines,

necessitating a shift in coastal management from historical restoration targets towards adaptive, function-based governance (Hershner and Havens 2008; Sarkar et al. 2021). In many large lagoons, changes in macrophyte dominance represent one of the most visible and management-relevant manifestations of these transformations.

The Chilika Lagoon, Asia's largest brackish water lagoon, provides a clear example of such long-term ecological

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reconfiguration. Since the early 1990s, the lagoon has undergone substantial hydrological alteration, culminating in the artificial opening of a new sea mouth in 2000 to restore tidal exchange and improve water quality (Sahu et al. 2014). Although this intervention enhanced salinity intrusion and ecological conditions in central and southern sectors, it also intensified spatial heterogeneity across the lagoon, particularly strengthening freshwater dominance, nutrient loading and sediment influx in the northern sector (Panigrahi et al. 2007; Srichandan et al. 2015; Finlayson et al. 2020).

From a coastal management perspective, the temporal expansion of *P. karka* presents a governance dilemma rather than a purely ecological one. *P. karka* is often categorized as invasive due to its capacity to displace native macrophytes, reduce habitat heterogeneity and modify trophic pathways (Gibbs 2000; Keller et al. 2018). Such concerns are particularly salient in a Ramsar-designated lagoon supporting fisheries, migratory birds of Central Asia flyway and seagrass ecosystems (Swain et al. 2022; Wails et al. 2021). Consequently, management responses have often emphasized control (e.g., burning) or removal. However, reducing catchment-derived nutrient inputs could weaken the environmental conditions that favour continued *P. karka* expansion and improve water quality and habitat suitability for native submerged macrophytes (Panigrahi et al. 2007; Swain et al. 2022). Consequently, the present macrophyte dominated state should not be assumed to be irreversible or inevitable solely because it has persisted for three decades. Its future stability may partly depend on the continuation of external nutrient inputs. However, because the present study did not quantify catchment-scale nutrient loads or experimentally assess vegetation responses to nutrient reduction, this pathway is treated as management hypothesis requiring target monitoring and evaluation.

At the same time, *P. karka* stands can support sediment stabilization, nutrient retention, trace-metal accumulation and carbon and nitrogen storage under low-salinity, organic rich conditions (Behera et al. 2018; Nazneen et al. 2022; Akadiri et al. 2024). These biogeochemical functions should be evaluated independently of the degree of hydrological modification and do not by themselves establish conservation value (Behera et al. 2018; Nazneen et al. 2022; Akadiri et al. 2024). In nutrient-enriched northern Chilika, these functions may influence sediment and nutrient dynamics, although their magnitude relative macrophyte habitats or less modified sectors were not assessed. This dual role generates a clear management trade-off. Continued expansion of *P. karka* may exacerbate biodiversity displacement and habitat homogenization over time, whereas large-scale removal could undermine existing regulating services that have developed over decades (Hershner and Havens 2008; Theuerkauf et al. 2017). The central management question, therefore, is not whether *P. karka* should be viewed simply as a threat or a benefit, but how its long-term expansion from 1991 to 2025 can be incorporated into adaptive, spatially explicit lagoon management strategies.

Importantly, recognition of the regulating functions associated with *P. karka* does not imply ecological equivalence with historical lagoon conditions, nor does it mean that carbon and nitrogen accumulation, sediment stabilization or trace-metal retention compensate for losses of biodiversity, habitat heterogeneity or native-community structure (Hershner and Havens 2008; Wails

et al. 2021; Swain et al. 2022). Prioritizing these functions over biodiversity or proximity to reference conditions would constitute a normative management choice (Finlayson et al. 2020). Such a choice should therefore be considered only after evaluating restoration feasibility, the potential to reduce external nutrient inputs, the degree to which hydrological conditions can be rehabilitated, the potential for native-community recovery and the ecological consequences of retention, containment or removal (Theuerkauf et al. 2017; Sarkar et al. 2021; Swain et al. 2022).

Therefore, the overarching objective of this study is to inform adaptive coastal lagoon management by evaluating the functional role of *P. karka* in the context of its long-term expansion (1991–2025) under altered hydrological and nutrient regimes in the Chilika Lagoon. Specifically, we aim to assess how decadal-scale changes in *P. karka* distribution translate into ecosystem service benefits and ecological trade-offs that are relevant to spatial planning and governance. The specific objectives are to (i) assess hydrological and water-quality conditions associated with present-day *P. karka* habitats to identify environmental drivers that have supported its long-term expansion across the lagoon, (ii) quantify sediment carbon and nitrogen stocks within *P. karka* habitats to evaluate how three decades of macrophyte dominance contribute to climate change mitigation and nutrient regulation services, (iii) evaluate the trace metals bioindicator potential of *P. karka* for long-term environmental monitoring in river-influenced lagoon sectors, (iv) characterize population demography and growth dynamics of *P. karka* to determine whether current conditions continue to factor expansion for indicate stabilization following decades of establishment and (v) integrate long-term spatial expansion (1991–2025) biogeochemical functions and population dynamics into a conceptual management decision framework that distinguishes among restoration, nutrient-source reduction, hydrological rehabilitation, containment, staged removal, monitored temporary retention and periodic reassessment. This integrated framework is intended to support spatially explicit and adaptive management of *P. karka* while ensuring that persistence and ecosystem functioning are not interpreted as substitutes for biodiversity conservation or restoration where these remain feasible. By explicitly embedding temporal change into the analysis, this study evaluates *P. karka* as a persistent invasive macrophyte within an alternative ecological configuration produced by sustained environmental modification. Persistence is treated here as a management consideration rather than evidence of ecological desirability, conservation equivalence or change in invasion status.

2 | Materials and Methods

2.1 | Study Area

The study was conducted in the Chilika Lagoon (a Ramsar wetland), Asia's largest brackish water lagoon (1165 km²), located along the east coast of India (Figure 1). The lagoon exhibits strong spatial heterogeneity driven by hydrological connectivity, freshwater inflow from distributaries and tidal exchange with the Bay of Bengal. Since the early 1990s, the ecological health of the lagoon has been degrading, and to restore the ecological functions, an artificial opening of a new sea mouth in 2000 was

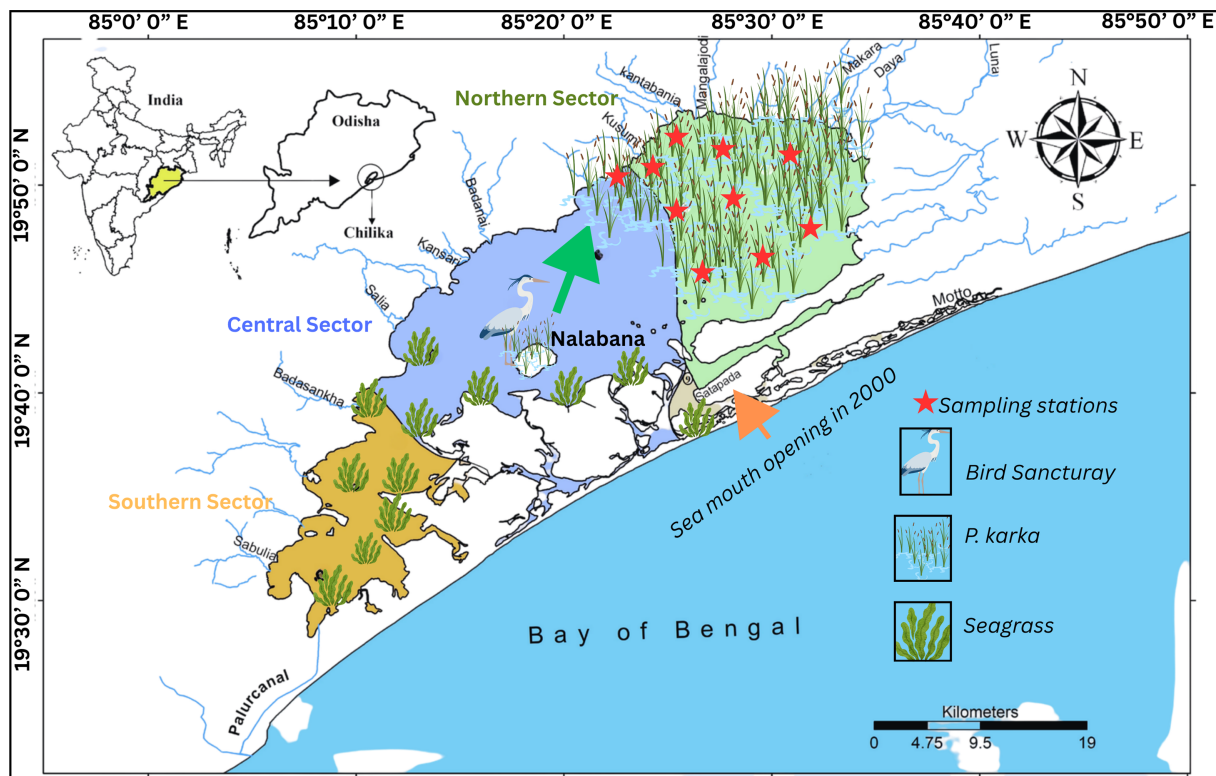


FIGURE 1 | Map of the study locations showcasing the presence of *Phragmites karka* in the northern sector of the Chilika lagoon, Odisha along with other macrophytes such as seagrasses. The orange arrow indicates the opening of sea mouth in the Year 2000, which led to the migration (green arrow) of *P. karka* from the Nalabana bird sanctuary towards the northern sector of the lagoon.

carried out by the Chilika Development Authority (CDA) (Swain et al. 2022). Since then, the lagoon has experienced pronounced shifts in salinity, sediment dynamics and nutrient regimes, especially in the northern sector. This sector has progressively become freshwater-dominated in the northern sector and nutrient-enriched, creating favourable conditions (Acharyya et al. 2023) for the expansion of emergent macrophytes, i.e., *P. karka*, covering an area of more than 86.11 km² (Bhatta and Patra 2020; Finlayson et al. 2020; Panigrahi et al. 2007). The northern sector receives river and catchment-derived nutrient inputs, which vary seasonally with monsoonal run-off and may be retained under restricted water exchange and high sediment accumulation (Srichandan et al. 2015; Finlayson et al. 2020).

2.2 | Long-Term Mapping of *P. karka* Expansion (1991–2025)

In the present work, we used long-term observations and a multicriteria approach to distinguish *P. karka* from surrounding vegetation (Figure 2), such as agricultural crops, deep open water, floating plants or dry terrestrial grasses. To do that, we used open-source Landsat datasets with annual seasonal median composites and three spectral indices.

2.2.1 | Satellite Data and Preprocessing

To quantify the long-term spatial dynamics of *P. karka*, multi-temporal Landsat imagery was used to map the extent of emergent vegetation over a 35-year period (1991–2025). Landsat-5

Thematic Mapper (TM), Landsat-7 Enhanced Thematic Mapper Plus (ETM+) and Landsat-8/9 Operational Land Imager (OLI) datasets were acquired at 30-m spatial resolution from the US Geological Survey (USGS) Earth Explorer as Level-2 surface reflectance products. These products are geometrically and atmospherically corrected and suitable for time-series analysis (Ilori et al. 2019; Teixeira Pinto et al. 2020). To ensure high agreement with the field validation campaign in January 2025, the temporal window has been narrowed, and only images from the dry season (January–March) for each corresponding year have been selected. Further, to avoid spectral noise induced by aerosol scattering or localized convection formation, and to haze and cover the wetland environment, we used a rigorous screen-level meta filter and restricted the analysis to scenes with a total cloud cover of less than 5%. A scan line failure occurred in the Landsat 7 sensor on 31 May 2003 and was addressed using median spatial interpolation (with a 1.5-pixel square neighbourhood kernel) to fill data voids before generating the image composites. All image processing was performed using Google Earth Engine (GEE) cloud-computing platform.

2.2.2 | Spectral Indices-Based Vegetation Mapping

2.2.2.1 | Normalized Difference Vegetation Index (NDVI). The NDVI was calculated for each selected image using standard formulations, with sensor-specific band assignments (Misra et al. 2020; Wu et al. 2017). Monthly NDVI layers were composited using a median reducer to generate a representative seasonal NDVI raster for each target year. This approach reduced the influence of residual cloud



(a) *P. karka* habitats with water hyacinth weeds



(b) Channels within *P. karka* habitats



(c) *P. karka* stems used as bundles for various fishing activities

FIGURE 2 | Representative *P. karka* habitats and community use in Chilika lagoon, India. (a) Natural *P. karka* habitat with water hyacinth, (b) dredged channel through *P. karka* stands used for boat passage and (c) bundled *P. karka* stems used as poles in fishing activities.

contamination and short-term environmental variability (Lambin and Strahler 1994). To capture long-term trends while maintaining consistency across sensors, NDVI composites were generated at annual intervals from 1991 to 2025. Temporally

stacked band composites were also produced for cross-validation and to ensure spectral consistency across Landsat sensors.

2.2.2.2 | Enhanced Vegetation Index (EVI). EVI was calculated to estimate the high-biomass structural canopy while minimizing soil background noise and resistance to saturation over dense emergent plant beds.

$$EVI = 2.5 \times \frac{NIR - Red}{NIR + 6.0 \times Red - 7.5 \times Blue + 1.0}$$

NIR (Near Infrared), Red and Blue are spectral bands of the respective Landsat satellite sensors.

2.2.2.3 | Modified Normalized Difference Water Index (MNDWI). The MNDWI index was used to demarcate land and water surfaces and their transitions, isolating deep-water surfaces from water-saturated mudflats and emergent vegetation zones. To calculate MNDWI, we used the Green and short-wave infrared (SWIR) bands using the following equation:

$$MNDWI = \frac{Green - SWIR1}{Green + SWIR1}$$

After that, the final spatial extent of *P. karka* was mapped by intersecting empirical threshold methods.

$$Extent = (NDVI > 0.32) \cap (EVI > 0.18) \cap (MNDWI < 0.0)$$

By doing so, we have filtered out low vegetative presence and retained only high-density biomass wetland vegetation, which shows a characteristic signature of *P. karka* (see samples of indices and extent for 2025 in Figure S1).

2.2.3 | Classification and Field Validation

Threshold-based classification was applied to delineate *P. karka* from NDVI and EVI composites. Threshold values were determined through extensive field validation conducted in January 2025 across the northern sector of the lagoon, where the presence and density of *P. karka* were systematically recorded. Field observations indicated that *P. karka* stands consistently corresponded to NDVI values ranging from 0.25 to 0.65, with lower values representing sparse stands and higher values representing dense emergent vegetation. Post processing steps were applied to reduce classification noise, including the removal of isolated patches smaller than 1800 m², which typically represented mixed pixels or edge artefacts rather than ecologically meaningful vegetation cover.

2.2.4 | Temporal Change Analysis

Changes in *P. karka* spatial extent were quantified for successive time intervals between 1991 and 2025. Absolute and relative area changes were calculated and interpreted in relation to documented salinity regimes, catchment-derived nutrient enrichment, hydrological modification and extreme events reported in the literature. Because consistent long-term nutrient data were unavailable, nutrient influences were evaluated qualitatively and were not treated as direct causal predictors of mapped

vegetation index. This long-term analysis provided the temporal context for evaluating present-day ecosystem functions and management trade-offs associated with *P. karka* dominance.

2.3 | Field Sampling

Field sampling was conducted at 10 representative *P. karka* habitats across the northern sectors of the lagoon during the postmonsoon season (January 2025). Sampling locations were selected to capture spatial variability in hydrological connectivity, salinity and sediment characteristics and were georeferenced using a handheld GPS (Figure 1). Sediment core, plant and water samples were collected at all sampling sites. However, sediment cores were collected from areas with water depth of less than 1 m. In many places, *P. karka* stands with water depth exceeding 1 m, which is not feasible for sampling due to limited accessibility and deeper water conditions.

2.4 | Water-Quality Analysis

At each station, surface water, physicochemical parameters (pH, temperature, total dissolved solids (TDS), salinity, electrical conductivity (EC) and oxidation–reduction potential (ORP)) were measured in situ using a multiparameter probe (ORION Thermo Scientific). Triplicate water samples were collected in presterilized plastic bottles (50-mL HDPE bottles) for nutrients and trace-metal analysis separately filtered with 0.45- μ m polycarbonate filter paper. After filtration, samples fixed with nitric acid (14-M Ultrapure) for metals and nonacidified samples for anions were preserved in ice and transported to the laboratory under cold and dark conditions. Major anions such as fluoride (F^-), chloride (Cl^-), bromide (Br^-) and nutrients (nitrate (NO_3^-) and sulphate (SO_4^{2-})) were analysed using ion chromatography systems (883 Basic IC Plus, Metrohm). Trace metals were measured using inductively coupled plasma-optical emission spectrometry (ICP-OES; 5110 Agilent). All concentrations were compared across stations to characterize water-quality gradients associated with *P. karka* habitats. Water-quality parameters were measured to characterize environmental conditions supporting long-term macrophyte persistence and to assess their implications for habitat suitability in freshwater-dominated lagoon sectors.

2.5 | Sediment Sampling and Biogeochemical Analysis

Sediment cores were collected at each station (up to 1 m) using a stainless steel corer (150 cm long and 5 cm), sectioned at 5-cm intervals in the field, labelled and stored in a zip-lock bag, placed in dark boxes and transported to the laboratory for further analysis. Samples were oven-dried at 60°C for 48 h, homogenized and analysed for Dry Bulk Density (DBD), organic matter content in a muffle furnace (Scientech: SE-130) at 500°C for 4.5 h (using loss on ignition method) and total carbon (C), nitrogen (N) and sulphur (S) using an elemental analyser (Elementar Vario MACRO cube) following the Blue Carbon Manual (Howard et al. 2014). Trace-metal concentrations in sediment were determined using the aqua regia (HCl: HNO₃ in a 3:1 ratio) method, utilizing a microwave digestion

system (Multiwave pro, Anton Paar), with the power set to 1300 W for a 20 min ramp and a 60-min hold time. After digestion, the solution was diluted, filtered and analysed in ICP-OES (Mishra et al. 2024). Sediment C and N stocks were quantified to assess relevant ecosystem function related to climate regulation and nutrient limitation.

2.6 | Plant Biomass and Metal Analysis

To assess metal accumulation in *P. karka* tissues and to evaluate its role as a bioindicator of land-derived and redox-sensitive contaminants in freshwater-influenced lagoon habitats, plant samples were hand collected from the locations where the sediment cores were collected. Triplicate plant samples were collected from each station, washed with tap water followed by distilled water to remove any sediment and debris and then separated into leaves, stems, floating roots and roots. Each plant section was oven-dried at 60°C for 48 h, homogenized and analysed for elemental composition (C, N and S) following the same methods as described for sediment (see Section 2.5). Trace-metal concentrations in plant tissues were determined by microwave digestion using only nitric acid, with the power set to 900 W for a 20-min ramp and a 60-min hold, followed by ICP-OES analysis (Mishra et al. 2024). Biota-Sediment Accumulation Factors (BSAF) were calculated to assess metal uptake efficiency (Mishra et al. 2019).

2.7 | Population Dynamics of *P. karka*

Population demography of *P. karka* was assessed using an adapted reconstruction approach previously adopted to rhizomatous seagrasses to estimate shoot age, recruitment and population growth (Duarte et al. 1994; Mishra, Rasheed, and Farooq 2025). Ten individual plants were hand collected from each of the 10 stations because dense stands, soft sediment and water depth restricted quadrat-based sampling, giving a total of 100 plants. Each plant was carefully uprooted to retain the entire roots and attached rhizomes. In the laboratory, consecutive internode lengths were measured with a Vernier calliper and plotted against internode position. Recurring modes in internode lengths were used to estimate the leaf-production interval (i.e., plastochrone interval), following established reconstruction principles (Mishra and Apte 2020; Mishra, Rasheed, and Farooq 2025). The estimated plastochrone interval was 29.68 days for *P. karka*. Long-term recruitment was estimated using a negative exponential decay model, whereas present recruitment, mortality and net population growth were derived under the near steady-state assumption of population demographic equilibrium (Cunha and Duarte 2004; Mishra et al. 2021).

2.8 | Statistical Analysis

Statistical analysis was conducted separately for each response variable to test spatial differences in water quality ($n=3$ replicates per station), sediment properties ($n=3$ replicates per station), plant traits ($n=3$ replicates per organ per station) and metal accumulation ($n=3$ replicates per organ per station). All data were prechecked for normality (Shapiro–Wilk

test) and homogeneity of variance (F -test). Variables satisfying these assumptions were compared among stations using one-way ANOVA, followed by Tukey's post hoc HSD test when the ANOVA was significant. Linear regression was used to examine relationship between sediment OM versus sediment N, C and S, whereas Pearson correlations tested associations between sediment variables (OM, C or N, DBD) on sediment C and N stocks. Exponential decay regression (single, two-parameter) model was used to estimate the long-term average recruitment rate (R). The confidence limit allowed its statistical comparison to the present recruitment rate (R_0) as described in Fourqurean et al. (2003). All statistical analyses were carried out using GraphPad PRISM (version 11.1.0), and graphs (except GIS images) and infographics were generated using Canva (1.124.1). Results are presented as mean $\pm$ standard deviation (SD).

2.9 | Development of the Management Decision Framework

A qualitative, evidence-based management decision framework was developed by synthesizing four evidence streams generated in this study; (i) long-term spatial persistence and expansion of *P. karka* from 1991 to 2025; (ii) present-day hydrological, salinity, nutrient and sediment conditions; (iii) sediment carbon and nitrogen storage and trace-metal accumulation; and (iv) population recruitment and persistence. These findings were evaluated alongside published evidence on invasive-macrophyte management, ecosystem service trade-offs, biodiversity conservation and restoration in Chilika lagoon and comparable wetlands (Hershner and Havens 2008; Finlayson et al. 2020; Sarkar et al. 2021; Wails et al. 2021).

Management conditions were organized according to eight criteria; (i) feasibility of native-macrophyte recovery; (ii) potential to reduce catchment nutrient inputs; (iii) biodiversity sensitivity; (iv) reversibility of hydrological modification; (v) constraints on restoration; (vi) risks of sediment, nutrient or contaminant mobilization during removal; (vii) expansion towards sensitive habitats; and (viii) changes in ecological or socio-economic conditions. Each condition was linked to a corresponding management response, including restoration, nutrient-source reduction, hydrological rehabilitation, containment, progressive or staged removal, monitored temporary retention and periodic reassessment. The framework is intended as qualitative decision support and was not treated as a quantitatively validated or predictive management model.

3 | Results

3.1 | Long-Term Spatiotemporal Expansion of *P. karka* (1991–2025)

Multidecadal Landsat analysis revealed pronounced temporal variability in the spatial extent of *P. karka* in the northern sector of the Chilika Lagoon over the last 35 years (1991–2025) (Figure 3, Figure S2 and Table S1). This time series indicated that *P. karka* exhibited alternating phases of rapid expansion and minimal contraction rather than an exponential increase.

Between 1991 and 1995, *P. karka* cover remained relatively stable, with a marginal increase of $\sim 1.4\%$. This was followed by a period of dramatic expansion between 1995 and 2001, during which *P. karka* extent increased by approximately 133% (Figure 3, Figure S2 and Table S1), coinciding with persistently low-salinity conditions (1.7 psu) in the northern sector of the lagoon.

Following the opening of the new sea mouth in 2000, the extent of *P. karka* increased slightly ($\sim 3\%$), followed by a further increase of $\sim 18\%$ between 2005 and 2009. This expansion occurred despite increased marine influence, rising salinity and suitability in the northern sector. *P. karka* nevertheless remained well above its pre-1995 extent, indicating the persistence of established stands. From 2010 to 2015, its extent increased again by a further 22%, even under moderately higher salinity conditions (> 5 psu). During the most recent decade (2015–2025), the spatial extent fluctuated interannually but remained above 80 km², reaching approximately 8611 ha in 2025 (Figure 3). These patterns indicate that *P. karka* has shifted from rapid expansion to a state of long-term spatial persistence within freshwater-influenced northern sector of Chilika lagoon.

3.2 | Spatial Correspondence Between Mapped *P. karka* Extent and Present-Day Habitat Conditions

Field sampling sites selected for biogeochemical and population analyses were located within areas consistently identified as *P. karka* dominated across multiple mapping periods (2015–2025), representing long-established habitats rather than recently colonized patches (Figure 3, Figure S2). Persistent *P. karka* habitats were spatially confined to low-energy, freshwater-influenced zones, characterized by increased depths and high sediment accumulation.

3.3 | Water-Quality Gradients With Long-Established *P. karka* Habitats

Water-quality measurements across long-established *P. karka* habitats exhibited relatively consistent freshwater-dominated conditions (Table 1, Table S2). Salinity remained uniformly low across sampling stations, consistent with freshwater-dominated conditions. Negative ORP values indicated reducing conditions. Nutrient concentrations exhibited limited variation among stations, suggesting uniform nutrient availability across sampled habitats. Metals were below-detection limits in the surface water samples at all stations (Table 1).

3.4 | Sediment Biogeochemistry and Scaling of Carbon and Nitrogen Stocks Using Mapped Extent

Sediment characteristics from *P. karka* habitats exhibited high OM content, low DBD and relatively low C:N ratios across stations. Sediment C stocks averaged 50.09 ± 18.11 Mg C ha⁻¹, whereas N stocks averaged 4.81 ± 1.60 Mg N ha⁻¹

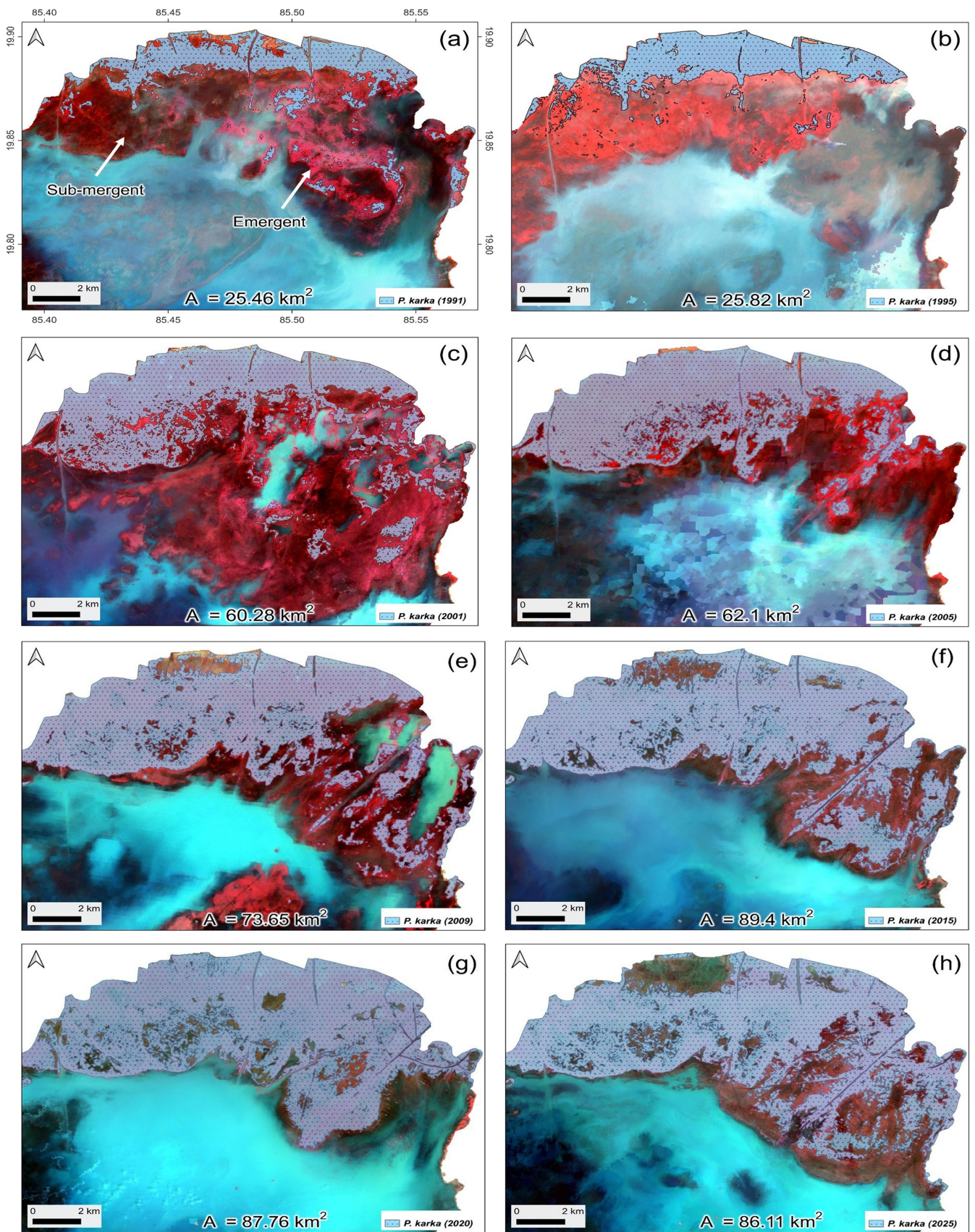


FIGURE 3 | Spatiotemporal map of the *P. karka* extent in the Northern Sector of the Chilika Lagoon. (background images are Landsat satellite imagery in True Colour Combination; FCC).

TABLE 1 | Physical parameters of water samples recorded from the study locations of *Phragmites karka* habitats from the Chilika lagoon, Odisha. Statistical significance ($p < 0.05$) was tested using one-way ANOVA and p -values are presented here. Check Table S2 for more details of the one-way ANOVA analysis. Total dissolved solids (TDS), electrical conductivity (EC), oxidation–reduction potential (ORP), fluoride (F^-), chloride (Cl^-), nitrate (NO_3^-) and sulphate (SO_4^{2-}).

Variable	Stations										p value
	1	2	3	4	5	6	7	8	9	10	
pH	8.10 ± 0.30	8.33 ± 0.43	8.90 ± 0.43	7.55 ± 0.40	7.46 ± 0.38	9.01 ± 0.40	9.52 ± 0.42	9.71 ± 0.13	10.21 ± 0.18	8.26 ± 0.20	<0.0001
Temp. (°C)	21.7 ± 0.34	21.8 ± 0.1	21.5 ± 0.1	22.09 ± 0.08	23.45 ± 0.23	21.32 ± 0.08	21.4 ± 0.45	21.53 ± 0.05	22.43 ± 0.05	23.06 ± 0.05	<0.0001
TDS (mgL ⁻¹)	3.84 ± 0.03	2.84 ± 0.10	1.28 ± 0.22	2.08 ± 0.97	1.68 ± 0.25	1.03 ± 0.01	1.32 ± 0.02	1.02 ± 0.01	2.02 ± 0.01	1.24 ± 0.29	<0.0001
Salinity (psu)	3.71 ± 1.05	3.71 ± 1.05	2.28 ± 0.16	2.49 ± 0.01	2.13 ± 0.05	3.73 ± 0.35	4.17 ± 0.15	4.18 ± 0.17	3.64 ± 0.43	3.15 ± 0.05	<0.0001
EC (S m ⁻¹)	869.7 ± 124.6	801.8 ± 206	904.8 ± 61.83	954.22 ± 87.34	415.7 ± 48.76	2021 ± 134.2	2693 ± 496.9	2173 ± 123	1868 ± 92.73	1079 ± 34.65	<0.0001
ORP (mV)	-42.57 ± 5.50	-129.7 ± 0.57	-124.4 ± 4.14	-306.8 ± 30.95	-19.4 ± 5.85	-211.6 ± 67.94	-191.33 ± 90.65	-145 ± 8.14	-265.9 ± 32.1	-118.6 ± 48.2	<0.0001
F ⁻ (mgL ⁻¹)	0.17 ± 0.008	0.36 ± 0.003	0.23 ± 0.003	0.37 ± 0.03	0.31 ± 0.006	0.38 ± 0.01	0.35 ± 0.01	0.38 ± 0.06	0.43 ± 0.01	0.2 ± 0.01	<0.0001
Cl ⁻ (mgL ⁻¹)	288.8 ± 26.41	2283 ± 10.52	767.6 ± 14.97	1756 ± 6.2	1477 ± 9.47	749.8 ± 0.93	807.7 ± 2.77	779.4 ± 1.05	669.2 ± 1.79	389.9 ± 1	<0.0001
NO ₃ ⁻ (mgL ⁻¹)	0.83 ± 0.29	0.49 ± 0.10	0.56 ± 0.31	0.47 ± 0.13	0.38 ± 0.08	0.87 ± 0.46	0.90 ± 0.25	0.54 ± 0.41	0.68 ± 0.03	0.86 ± 0.31	0.2263
SO ₄ ²⁻ (mgL ⁻¹)	14.45 ± 0.78	249 ± 1.82	19.78 ± 0.42	273.1 ± 4.32	161.18 ± 2.66	11.21 ± 0.06	52.24 ± 0.25	56.42 ± 0.7	29.02 ± 0.16	58.92 ± 0.32	<0.0001

TABLE 2 | Physical parameters of sediment samples recorded from the study locations of *P. karka* habitats from the Chilika Lagoon, Odisha. Statistical significance ($p < 0.05$) was tested using one-way ANOVA, and p -values are presented here. Check Table S3 for more details of the one-way ANOVA analysis. Dry bulk density (DBD g cm⁻³), organic matter (OM%), total carbon (C%), total nitrogen (N%), total sulphur (S%), C:N, C stocks (Mg C ha⁻¹) and N stocks (Mg N ha⁻¹).

Variable	Stations										p
	1	2	3	4	5	6	7	8	9	10	
DBD (g/cm ⁻³)	0.27 ± 0.09	0.25 ± 0.11	0.35 ± 0.08	0.39 ± 0.11	0.26 ± 0.06	0.13 ± 0.07	0.24 ± 0.07	0.30 ± 0.12	0.17 ± 0.04	0.79 ± 0.32	<0.0001
OM (%)	14.36 ± 3.27	14.90 ± 3.99	13.04 ± 1.64	14.80 ± 2.41	13.69 ± 1.58	15.89 ± 1.27	15.26 ± 1.74	12.47 ± 2.85	14.99 ± 1.34	7.07 ± 2.38	<0.0001
C (%)	3.38 ± 1.03	3.60 ± 1.67	3.61 ± 1.25	3.41 ± 1.53	2.70 ± 0.53	4.12 ± 0.55	3.73 ± 1.1	3.21 ± 1.35	3.92 ± 0.61	1.55 ± 0.75	<0.05
N (%)	0.36 ± 0.12	0.32 ± 0.1	0.38 ± 0.14	0.31 ± 0.12	0.25 ± 0.05	0.42 ± 0.04	0.33 ± 0.08	0.29 ± 0.12	0.39 ± 0.07	0.11 ± 0.06	<0.0001
S (%)	1.52 ± 0.14	2.49 ± 0.68	1.98 ± 0.48	1.71 ± 0.21	1.76 ± 0.33	1.62 ± 0.42	1.74 ± 0.21	1.74 ± 0.33	2.61 ± 0.94	0.71 ± 0.3	<0.0001
C:N	9.36 ± 0.63	10.97 ± 1.20	9.45 ± 0.72	11.21 ± 3.38	10.61 ± 0.78	9.88 ± 1.18	11.18 ± 1.75	11.22 ± 2.65	9.75 ± 0.58	14.93 ± 3.47	<0.0001
C stocks (Mg C ha ⁻¹)	80.23 ± 3.76	49.50 ± 11.05	61.33 ± 5.08	65.52 ± 3.62	36.19 ± 3.01	39.43 ± 10.45	24.26 ± 6.48	43.41 ± 1.20	32.34 ± 2.35	68.69 ± 24.82	<0.05
N stocks (Mg N ha ⁻¹)	8.41 ± 0.35	4.73 ± 1.10	6.43 ± 0.16	5.73 ± 0.31	3.48 ± 1.07	3.87 ± 0.65	4.25 ± 0.13	3.97 ± 0.22	3.30 ± 0.21	3.91 ± 1.23	0.62

(Table 2, Table S3). When scaled using the remotely sensed *P. karka* extent for 2025 (> 8611.2 ha), these values correspond to approximately 0.43 million Mg of sediment C and 41,420 Mg of sediment N within *P. karka* habitats across the lagoon. Sediment total N ranged from 0.11% to 0.42%, indicating N retention within established *P. karka* habitats, although nutrient sources and loading rates are not determined. This spatial scaling estimates the standing sediment carbon and nitrogen pools associated with the mapped extent of *P. karka* habitats in 2025.

3.5 | Trace-Metal Accumulation Patterns Linked to Habitat Persistence

Although dissolved metals were below-detection limit in surface waters, sediments within mapped *P. karka* habitats exhibited moderate enrichment for Co, Mn and Zn (Figure 4, Table S4). Plant tissue analysis revealed elevated concentrations of Mn, Ni Co and Na in roots and floating roots, with BSAF > 1 (Figure 5, Table S5). These findings document the accumulation of selected metals in sediments and plant tissues within long-established *P.*

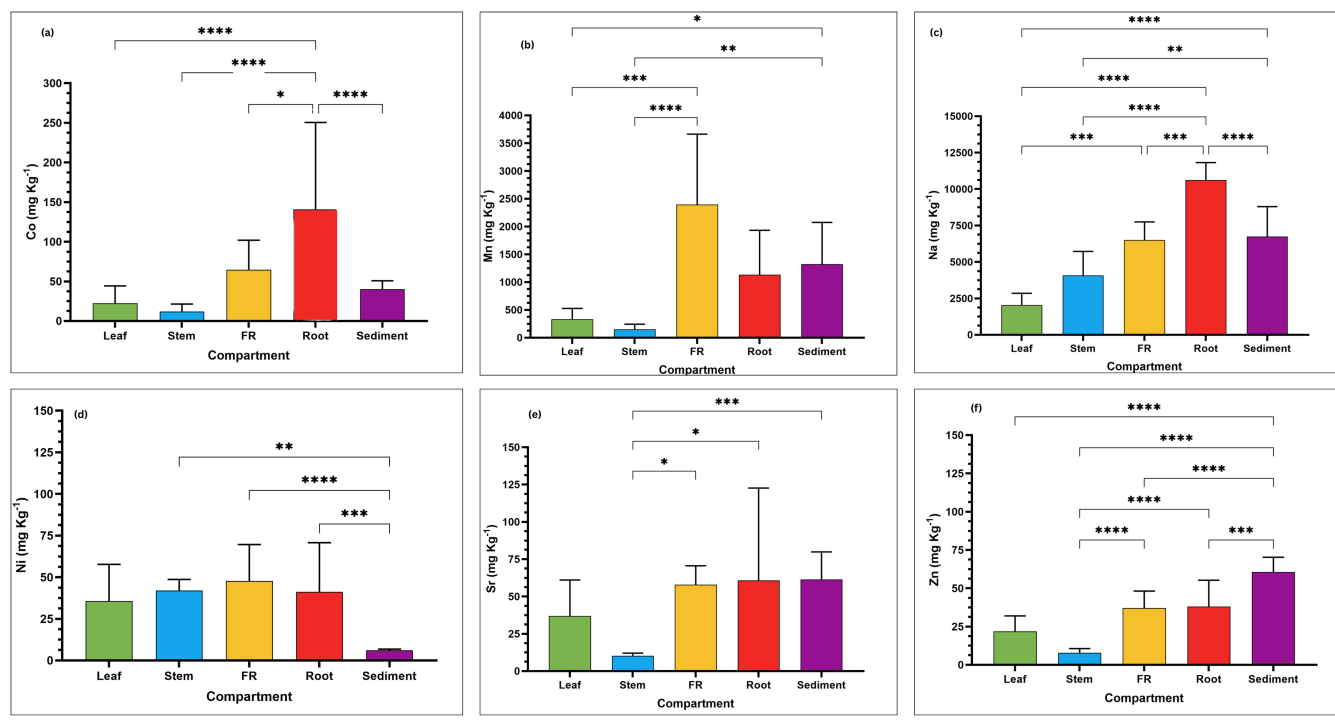


FIGURE 4 | Mean $\pm$ SD of metal concentration in plant tissues (leaf, stem, floating root (FR) and roots) and sediment across the *P. karka* habitat of the Chilika Lagoon, Odisha. Statistical significance ($p < 0.05$) was derived from one-way ANOVA analysis using compartments as fixed factors. ($p < 0.05$ *, $p < 0.001$ **, $p < 0.0001$ *** and $p < 0.00001$ ****). Note that Y-axis scale differs among panels.

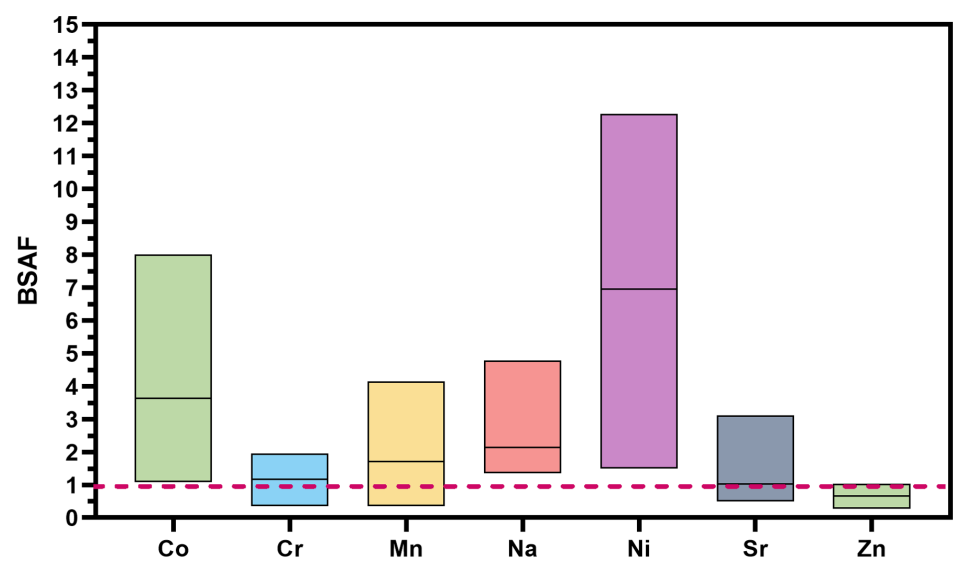


FIGURE 5 | Bar plots of biota-sediment Accumulation factor (BSAF) for various metals in the sediment and *P. karka* tissues of the Chilika Lagoon, Odisha. The pink dotted line indicates the BSAF threshold value of 1. See Table S5 for the range values of each trace metal.

karka habitats indicating that prolonged habitat persistence of *P. karka* functions as an effective sink for land-derived and redox-sensitive metals. However, the study did not compare metal accumulation with native-macrophyte habitats or less modified lagoon sectors.

3.6 | Population Demography With Long-Term Expansion Zones

Population demography analysis revealed a predominance of young shoots alongside a continuous age distribution, indicating active recruitment with long-established *P. karka* habitats (Figure 6; Table S6). The present recruitment rate exceeded long-term average recruitment, resulting in a positive population growth rate (Figure 6). Shoot age structure and longevity estimates further supported the conclusion that *P. karka* populations within the northern lagoon sector are stable and self-maintaining (Figure 6c). These demographic patterns are consistent with remote sensing evidence of long-term spatial persistence and indicate that *P. karka* dominance reflects structural integration into the lagoon ecosystem rather than episodic or transient colonization. The coupling of positive population growth with long-term spatial persistence suggests that *P. karka* is likely to remain dominant under current environmental conditions. However, this persistence does not alter its invasive status or imply ecological acceptance as a desirable component of the lagoon ecosystem.

3.7 | Context-Dependent Management Pathways

Integration of the spatial, environmental, biogeochemical and demographic evidence identified multiple management pathways, rather than a single lagoon-wide response to *P. karka* dominance (Figure 7). Areas where native-community recovery, nutrient reduction or practical hydrological rehabilitation remain feasible were linked to restoration, driver reduction and containment. Biodiversity-sensitive habitats and areas undergoing active expansion were linked to prevention of further spread and progressive removal. Controlled temporary retention was restricted to highly modified sectors where restoration is constrained and rapid removal may mobilize stored sediments, nutrients or contaminants. All management pathways incorporate monitoring and periodic reassessment as ecological and socio-economic conditions change.

4 | Discussion

4.1 | Decadal Expansion and Environmental Reinforcement of the *P. karka* Invasion

The long-term spatiotemporal patterns observed between 1991 and 2025 indicate that the persistence and expansion of *P. karka* in the northern sector of the Chilika Lagoon are maintained by sustained hydrological reorganization, freshwater influence and nutrient enrichment. This interpretation concerns the environmental drivers and duration of the invasion and does not imply that long-term establishment changes the species' invasive status. These patterns indicate a persistent and environmentally

reinforced invasion within a reconfigured lagoon system (Chambers et al. 1999; Theuerkauf et al. 2017). Long-term establishment therefore changes the feasibility and potential consequences of management, but not the invasive status of *P. karka* (Hershner and Havens 2008; Wails et al. 2021).

In the Chilika Lagoon, hydrological interventions associated with the artificial opening of the sea mouth in 2000 altered lagoon-wide salinity gradients and sediment dynamics (Panigrahi et al. 2007; Srichandan et al. 2015). Early expansion phases of *P. karka* coincided with persistently low-salinity conditions, consistent with experimental and field studies showing high freshwater tolerance and salinity plasticity in *P. karka* (Abideen et al. 2014; Nayak et al. 2020). However, the persistence and renewed expansion of *P. karka* after 2009, even under higher salinity, mirrors observations for *P. australis* in modified estuaries of North America and Europe, where established reed stands persist through feedback that decouples expansion from initial salinity thresholds (Chambers et al. 1999; Wails et al. 2021). In India, similar long-term expansions of *Phragmites* species have been reported from Chilika lagoon and other freshwater-dominated coastal wetlands, where reed proliferation has been linked to nutrient enrichment and altered hydrology rather than episodic disturbance alone (Nabi 2021; Swain et al. 2022). Hydrological modification and nutrient enrichment should not, however, be treated as equally reversible drivers. Reversal of lagoon-scale hydrological changes may be technically difficult and could have consequences for fisheries, salinity regimes and other lagoon habitats (Finlayson et al. 2020). In contrast, reducing external nutrient inputs from the catchment may provide a more feasible intervention for weakening the conditions that support *P. karka* productivity and expansion (Panigrahi et al. 2007; Sarkar et al. 2021). Nutrient reduction could also improve water quality and increase opportunities for native submerged-macrophyte recovery (Acharyya et al. 2023). Therefore, the persistence observed in this study should be interpreted as conditional or continuation of the prevailing environmental regime rather than as evidence that the current state is permanently fixed. These patterns indicate a persistent and environmentally reinforced invasion within an altered lagoon system. However, reducing external nutrient inputs may alter the conditions supporting its dominance, meaning that persistence should not be interpreted as ecological inevitability. Future studies should quantify seasonal nitrogen and phosphorus loads and evaluate vegetation responses to nutrient-reduction interventions (Mishra, Watson, et al. 2025).

Within invasion science, persistence, spread, ecological impact and management feasibility represent related but distinct dimensions (Chambers et al. 1999; Theuerkauf et al. 2017; Wails et al. 2021). The present nutrient measurements represent a single postmonsoon survey and do not quantify seasonal nutrient fluxes, catchment-source contamination of nitrogen and phosphorus. Therefore, future research should quantify catchment nutrient loads, identify major nutrient sources and evaluate vegetation responses to nutrient-reduction interventions. Furthermore, long-term establishment does not confer native status, ecological desirability or conservation value. Rather, it may indicate a self-maintaining invasion in which control outcomes depend on environmental drivers, restoration potential and the ecological consequences of intervention (Sarkar

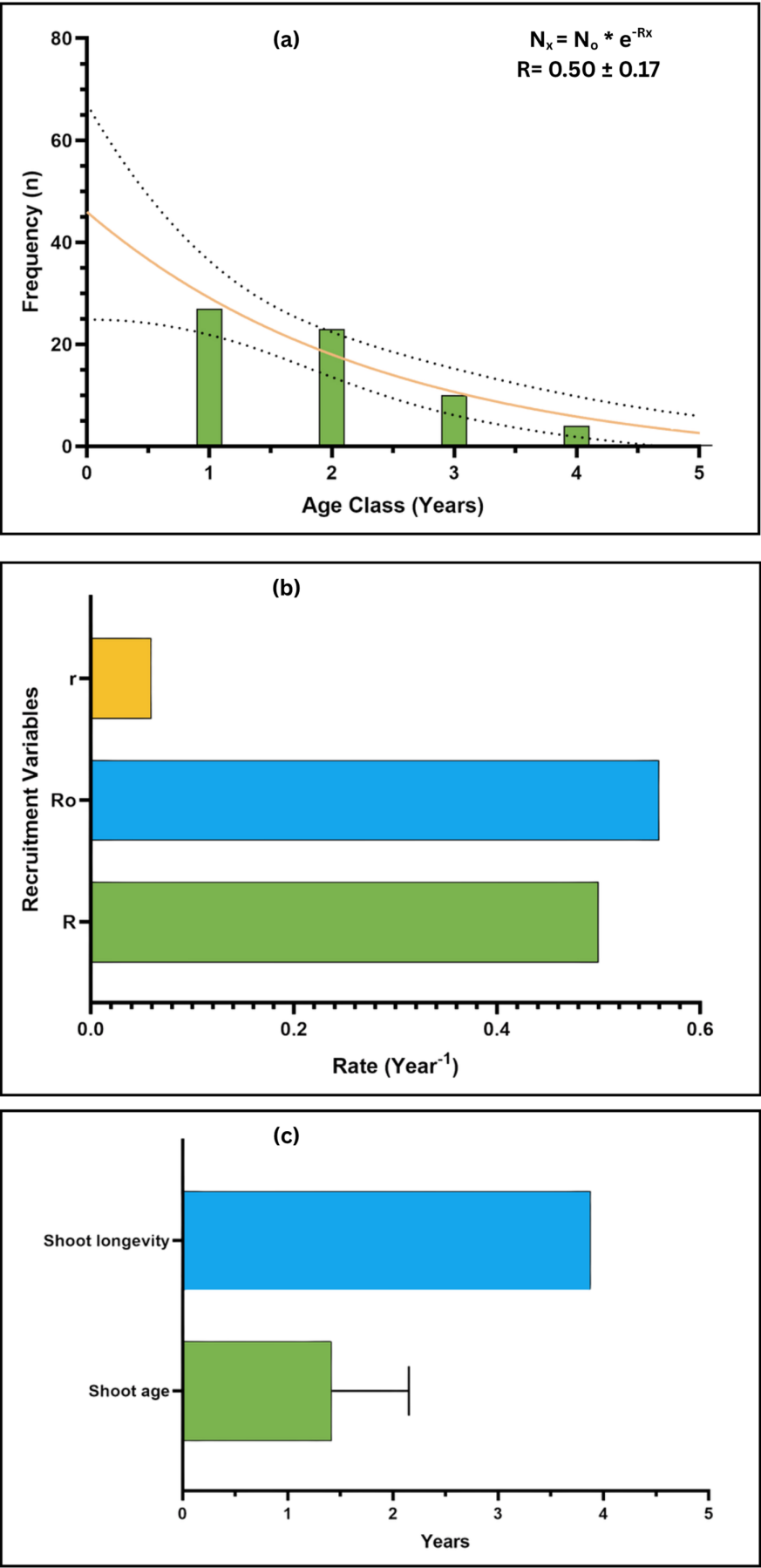


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FIGURE 6 | *P. karka* (a) age frequency distribution, (b) recruitment (long-term average (R), present recruitment (R_0) and growth rate (r)), and (c) shoot age and longevity derived using reconstruction techniques from the Chilika Lagoon, Odisha. The long-term average recruitment was estimated from the exponential decay regression line fitted to age frequency distribution mentioned at Table S6.

et al. 2021; Swain et al. 2022). Our findings therefore do not conflict with established invasion frameworks; *P. karka* remains an invasive macrophyte, but the appropriate management response should be determined by site-specific impacts, restoration feasibility and the risks associated with either retention or removal (Finlayson et al. 2020).

4.2 | Vegetation-Sediment Feedbacks Reinforce *P. karka* Persistence

The spatial persistence of *P. karka* in freshwater-influenced depositional, low-energy zones reflects feedback mechanisms that are well documented for *Phragmites* species globally. Dense reed stands reduce near-bed flow velocity, enhance sediment trapping and promote organic matter accumulation, leading to progressive modification of sediment structure (Chambers et al. 1999; Theuerkauf et al. 2017).

Field measurements from Chilika showing high OM content, low DBD and reducing sediment conditions within mapped *P. karka* habitats are consistent with studies from Indian coastal wetlands where *Phragmites* dominance has been shown to alter sediment biogeochemistry and microbial processes (Behera et al. 2018; Sarkar et al. 2021). Similar sediment-vegetation feedback has been reported from saltmarsh and estuarine wetlands in the Mediterranean and East Asia, where *Phragmites* expansion reinforces its own persistence through habitat engineering (Meyerson et al. 2000; Ogurcak et al. 2019). This feedback provides a mechanistic explanation for the long-term persistence of *P. karka* in the Chilika Lagoon, even during periods of increased salinity and hydrological variability (Figure S2).

4.3 | Sediment Carbon and Nitrogen Accumulation Within *P. karka* Stands

Sediment C and N stocks measured within *P. karka* stands averaged $50.09 \pm 18.11 \text{ Mg C ha}^{-1}$ and $4.81 \pm 1.60 \text{ Mg N ha}^{-1}$, respectively. These values represent habitat-specific standing stocks associated with established reed stands. *Phragmites* dominated wetlands can accumulate organic matter through high below-ground production, sediment trapping and reduced sediment resuspension (Carruthers et al. 2024; Windham et al. 2003). However, the present study did not measure carbon burial rates or greenhouse gas (CO_2 , CH_4 and N_2O) fluxes and therefore cannot directly determine climate-mitigation performance. This limitation is important because CO_2 and CH_4 effluxes can vary substantially among vegetated, unvegetated, tidally connected or restricted tropical coastal wetlands (Sasmito et al. 2026).

For local context, the mean sediment C stock measured within *P. karka* stands was lower than the approximately 127–129 Mg

C ha^{-1} reported for the upper 1 m of sediment in mixed seagrass meadows of Chilika lagoon (Ganguly et al. 2017; Mishra et al. 2023). This comparison is contextual rather than direct because the studies differed in habitat type, sediment characteristics, spatial design and analytical methods. Native macrophyte, unvegetated and less modified habitats were not sampled concurrently; therefore, the results do not establish the relative carbon-storage capacity or conservation value of *P. karka* stands compared with recognized blue carbon ecosystems. The C stocks measured within persistent *P. karka* habitats are consistent with evidence that long-established reed stands can accumulate sediment carbon under nutrient-rich conditions (Akadiri et al. 2024; Nabi 2021). However, this comparison should be interpreted cautiously because the studies differed in sediment characteristics, spatial settings and analytical design.

4.4 | Trace-Metal Accumulation and Bioindicator Potential of *P. karka*

The accumulation of metals in *P. karka* sediments and tissues reflects well-established metal sequestration pathways in *Phragmites* dominated wetlands. Globally, *Phragmites* species are known to preferentially accumulate redox-sensitive and land-derived metals such as Mn, Ni and Co, particularly under low-salinity and reducing conditions (Akhter et al. 2024; Bonanno and Orlando-Bonaca 2018). In India, *P. karka* has been widely documented as an effective phytoremediator and bioindicator in freshwater and brackish wetlands, showing high accumulation of Mn, Ni, Zn and Co, in below-ground tissues (i.e., roots) (Nabi 2021; Nazneen et al. 2022). Studies from Chilika Lagoon have also demonstrated contrasting metal accumulation patterns between *Phragmites* and seagrass ecosystems, with *Phragmites* showing greater sensitivity to terrestrial contamination sources (Mishra and Farooq 2022a; Nazneen et al. 2022). Evidence from the COVID-19 lockdown further indicates that reductions in anthropogenic activity can lower metal concentrations in Chilika Lagoon's surface waters and sediments, emphasizing the importance of pollution-source control alongside biomonitoring (Acharya et al. 2022; Mishra et al. 2024). The observed accumulation patterns support the potential use of *P. karka* tissues for monitoring selected metals in freshwater-dominated lagoon sectors. However, metal accumulation does not necessarily indicate improved ecosystem condition or confer greater conservation value, and this capacity was not compared with native vegetation or less modified habitats.

4.5 | Population Demography Indicates Continued Persistence of *P. karka* Under Current Environmental Conditions

Population demographic patterns observed for *P. karka* indicate active recruitment and sustained population renewal within

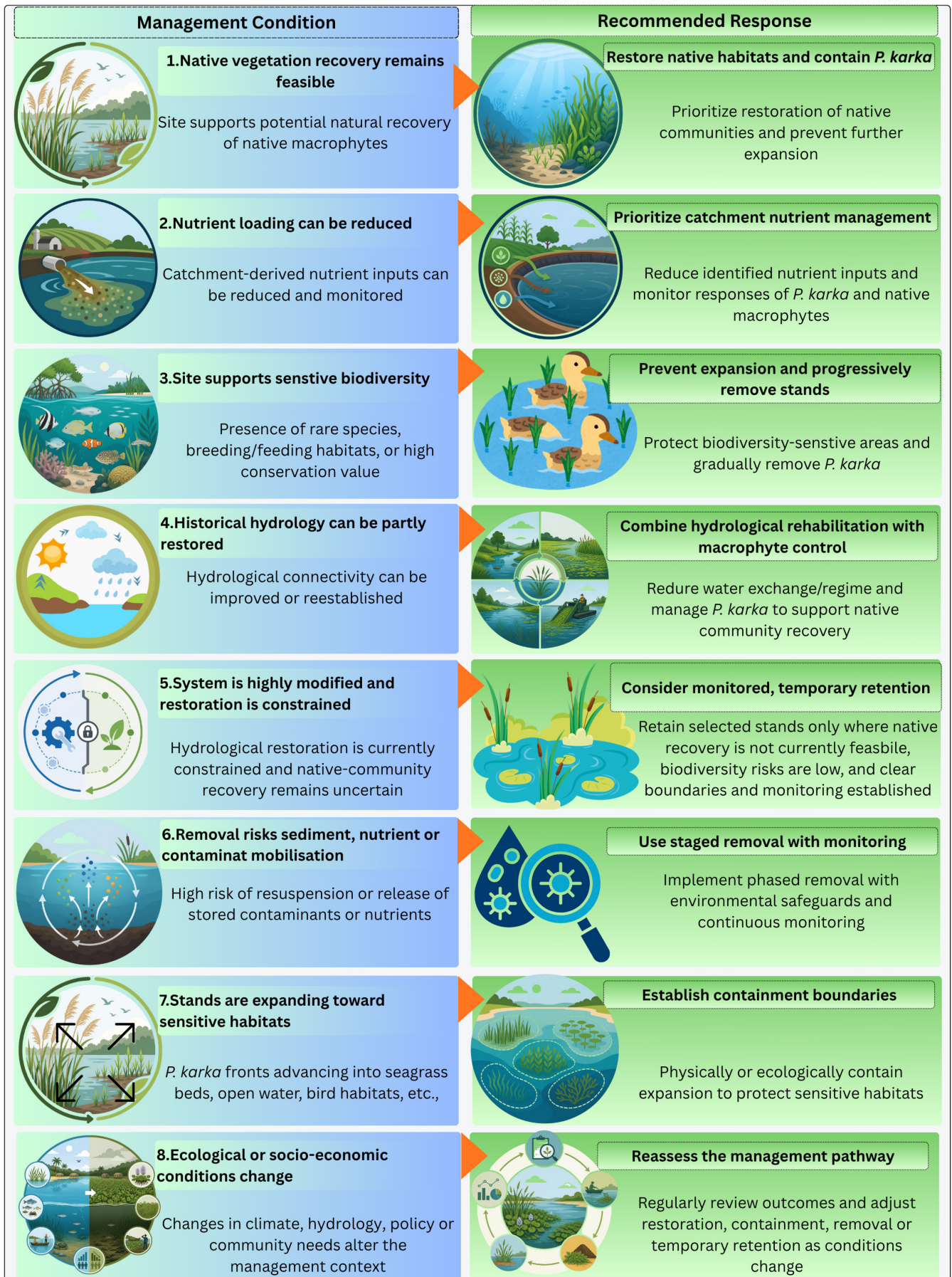


FIGURE 7 | Legend on next page.

FIGURE 7 | Context-dependent management framework for *P. karka* in Chilika Lagoon, India. The framework links site-specific ecological, hydrological and socio-economic conditions with management responses, including restoration, nutrient reduction, containment, staged removal, temporary retention and periodic assessment.

long-established habitats. Similar demographic resilience has been widely reported for *P. australis* population globally, where high recruitment rates and clonal growth allow rapid recovery following disturbance (Chambers et al. 1999; Fouad et al. 2025). In the Indian context, demographic studies on *Phragmites* are limited; however physiological and molecular studies on *P. karka* demonstrate high plasticity under salinity and nutrient stress, supporting its long-term persistence (Abideen et al. 2018; Nayak et al. 2020). The positive population growth observed in Chilika suggests that *P. karka* dominance is likely to persist under current hydrological or nutrient regimes. Persistence alone, however, does not alter the species' invasive status or establish its conservation value (Chambers et al. 1999; Wails et al. 2021). Rather, it indicates that management focused solely on repeated biomass removal is unlikely to produce durable outcomes unless the environmental drivers supporting expansion are also addressed (Hershner and Havens 2008; Sarkar et al. 2021; Swain et al. 2022). Because catchment nutrient loading may be more readily managed than lagoon-scale hydrological conditions, nutrient-source reduction should be evaluated as priority intervention before concluding that persistent *P. karka* dominance is unavoidable (Finlayson et al. 2020; Sarkar et al. 2021).

4.6 | Context-Dependent Management Pathways of *P. karka*

Management of persistent *Phragmites* invasion should not be framed as a binary choice between eradication and passive acceptance (Hershner and Havens 2008; Wails et al. 2021). In Chilika Lagoon, *P. karka* contributes to sediment stabilization, blue carbon and blue nitrogen storage, nutrient retention and trace-metal accumulation, whereas its continued expansion may reduce native macrophyte cover, open water habitat, habitat heterogeneity and biodiversity (Nazneen et al. 2022; Swain et al. 2022; Wails et al. 2021). These regulating functions do not establish ecological equivalence with historical lagoon conditions or compensate for biodiversity loss (Hershner and Havens 2008; Finlayson et al. 2020; Wails et al. 2021). These biogeochemical attributes represent only one component of management assessment and should not be interpreted as assigning greater conservation value to hydrologically modified or *P. karka*-dominated sectors. Biodiversity condition, habitat heterogeneity, native-community recovery potential and proximity to reference conditions must also be considered.

The proposed decision framework integrates restoration feasibility, catchment nutrient management, biodiversity sensitivity, hydrological rehabilitation, removal risks and socio-economic conditions to identify context-appropriate management responses for *P. karka* in Chilika Lagoon (Figure 7). The proposed management framework therefore evaluates multiple site-specific pathways rather than recommending general retention of *P. karka* (Figure 7). Where native-macrophyte recovery remains feasible, restoration and containment should

be prioritized (Finlayson et al. 2020; Acharyya et al. 2023). Where catchment nutrient inputs can be reduced, nutrient-source management should accompany vegetation control because repeated biomass removal alone is unlikely to provide durable outcomes unless the environmental drivers of expansion are also addressed (Sarkar et al. 2021; Swain et al. 2022). Nutrient-source reduction may also benefit native submerged macrophytes because anthropogenic nitrogen enrichment can increase sediment sulphide intrusion and physiological stress in tropical seagrasses (Mishra and Farooq 2025). This nutrient enrichment can also reduce seagrass meadow migration, population longevity and associated biodiversity, further supporting the need to address catchment nutrient inputs along *P. karka* control (Mishra, Rasheed, and Farooq 2025). In Chilika Lagoon, catchment nutrient reduction may present a more practicable first-line intervention than attempting to reverse major lagoon-scale hydrological changes. If nutrient reduction limits *P. karka* productivity or improves the recovery potential of native macrophytes, management pathways involving temporary retention should be reassessed. Conditional retention should therefore not be treated as permanent end point, but as an adaptive and reversible option that may change following improvements in catchment nutrient management (Hershner and Havens 2008; Sarkar et al. 2021). In biodiversity-sensitive habitats, including seagrass beds, bird-use areas and open water environments, further expansion should be prevented, and stands should be progressively removed (Finlayson et al. 2020; Acharyya et al. 2023; Swain et al. 2022). This precaution is particularly important for the vulnerable Indo-Pacific seagrasses such as *Halophila beccarii*, whose restricted distribution, limited dispersal, low genetic diversity and low competitive ability constrain its adaptive capacity and recovery following habitat alteration or in the case of Chilika Lagoon, competitive displacement (Mishra et al. 2026). However, where historical hydrology can be partly restored, hydrological rehabilitation should be combined with macrophyte control (Finlayson et al. 2020; Sarkar et al. 2021).

Native-species alternatives should also be evaluated before retaining invasive stands. Where native macrophytes can recover and provide sediment stabilization, nutrient regulation, habitat structure or other relevant ecological functions, active restoration should be preferred over continued dependence on *P. karka* (Ganguly et al. 2017; Finlayson et al. 2020; Acharyya et al. 2023). Controlled temporary retention may be considered only in highly modified sectors where restoration is demonstrably constrained, biodiversity risks are relatively low and rapid removal could mobilize sediments, nutrients or contaminants (Mishra and Farooq 2022a; Acharya et al. 2022; Theuerkauf et al. 2017). In these locations, retention should remain conditional, spatially bounded and regularly reassessed (Hershner and Havens 2008; Sarkar et al. 2021). Staged removal, containment boundaries and continued monitoring are therefore central components of the framework (Figure 7). This approach does not normalize persistent invasion; instead it identifies when restoration, containment, gradual removal or monitored

temporary retention provides the most defensible ecological and socio-economic outcomes (Hershner and Havens 2008; Mohanty et al. 2024).

4.7 | Implications for Chilika Lagoon Management and Limits of Transferability

The long-term patterns documented for *P. karka* in Chilika Lagoon are consistent with global trajectories of *Phragmites* expansion under sustained hydrological modification and nutrient enrichment. Similar outcomes have been reported from coastal lagoons and estuaries in Europe, North America, Africa and Asia, indicating that macrophyte dominance is a common response to altered coastal hydrology (Fouad et al. 2025; Ogurcak et al. 2019; Theuerkauf et al. 2017). By integrating multidecadal remote sensing with field-based biogeochemical and demographic evidence, this study provides a decision support framework for evaluating persistent *Phragmites* invasion. The framework does not advocate passive acceptance of invasive dominance. Instead, it prioritizes restoration and containment where these remain feasible, while recognizing that staged removal or monitored temporary retention may be necessary in sectors where ecological modification is severe and intervention risks are high (Hershner and Havens 2008; Sarkar et al. 2021). Within Chilika lagoon, the recommended management pathway should also be periodically revised as evidence emerges regarding the effectiveness of catchment nutrient reduction and the recovery potential of native communities. Application beyond Chilika lagoon requires case-by-case assessment of invasion impacts, restoration potential, native-species alternatives, ecosystem functions and socio-economic objectives (Finlayson et al. 2020; Mohanty et al. 2024). Such application also requires adequate species- and site-level ecological information, because data deficiencies can prevent defensible management decisions for ecologically important native-macrophyte ecosystems (Mishra and Farooq 2022b).

5 | Conclusion

The study provides a comprehensive, multidecadal assessment of the expansion, ecosystem functioning and management implications of *P. karka* in the Chilika Lagoon. By integrating 35 years of satellite-based mapping with field measurements of water quality, sediment biogeochemistry, metal accumulation and population demography, we demonstrate that *P. karka* expansion represents a persistent response to long-term hydrological modification and nutrient enrichment rather than a transient invasion.

The sampled *P. karka* stands contained substantial sediment blue carbon and nitrogen stocks and accumulated selected metals in sediments and plant tissues. These results document the biogeochemical attributes of established stands but do not demonstrate greater storage or retention than native macrophyte, unvegetated or less modified habitats, which were not sampled. These functions should therefore not be interpreted as evidence that hydrological modification increases ecological value or as justification for continued invasive dominance. High sediment carbon stocks highlight the contribution of emergent macrophytes

to climate regulation in lagoon environments where seagrasses are limited. Elevated metal accumulation in below-ground tissues confirms the value of *P. karka* as trace-metal bioindicators for long-term environmental monitoring.

Population demographic analyses indicate sustained recruitment and growth, suggesting that current hydrological and nutrient regimes favour *P. karka* persistence. These findings imply that natural decline is unlikely without substantial modification of underlying drivers. Importantly, the results highlight a clear management trade-off: Although extensive *P. karka* removal could destabilize sediments and release stored nutrients and contaminants, unchecked expansion may increase habitat homogenization and biodiversity displacement. These findings do not imply that the regulating functions of *P. karka* compensate for biodiversity loss, that persistent dominance represents a desirable conservation state or that long-term persistence changes its invasion status. The current state should instead be interpreted as an alternative ecological configuration produced by interacting hydrological, nutrient and sedimentary changes, the management of which requires explicit assessment of ecological trade-offs.

We recommend that effective management of *P. karka* in the Chilika lagoon should combine control of underlying drivers, containment of further expansion, restoration where feasible and selective retention only where clearly justified. In sectors where catchment nutrient reduction, hydrological rehabilitation and native-community recovery remain feasible, restoration and invasive-species control should remain management priorities. Selective retention should be considered only in heavily modified sectors where restoration is demonstrably constrained, biodiversity risks are relatively low and removal could cause substantial ecological or socio-economic harm. The proposed zonation approach is therefore a context-dependent strategy for Chilika Lagoon rather than a general justification for accepting invasive-macrophyte dominance in coastal wetlands.

Author Contributions

Anjalis Mishra: methodology, data curation, formal analysis, writing – review and editing, writing – original draft. **Shashi Kant Rai:** methodology, validation, visualization, writing – review and editing, software, formal analysis, data curation, writing – original draft. **Syed Hilal Farooq:** writing – original draft, writing – review and editing, investigation, conceptualization, methodology, supervision. **Amrit Kumar Mishra:** supervision, writing – review and editing, writing – original draft, conceptualization, investigation, funding acquisition, methodology, validation, visualization.

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Ethics Statement

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All the data generated in this study are presented either as tables and figures in the manuscript or in the [Supporting Information](#).

References

- Abideen, Z., H. W. Koyro, B. Huchzermeyer, M. Z. Ahmed, B. Gul, and M. A. Khan. 2014. "Moderate Salinity Stimulates Growth and Photosynthesis of *Phragmites karka* by Water Relations and Tissue Specific Ion Regulation." *Environmental and Experimental Botany* 105: 70–76. <https://doi.org/10.1016/j.envexpbot.2014.04.009>.
- Abideen, Z., M. Qasim, T. Hussain, et al. 2018. "Salinity Improves Growth, Photosynthesis and Bioenergy Characteristics of *Phragmites karka*." *Crop & Pasture Science* 69: 944–953. <https://doi.org/10.1071/CP18154>.
- Acharya, P., P. R. Muduli, M. Das, and A. K. Mishra. 2022. "Assessment of Total Petroleum Hydrocarbon Accumulation in Crabs of Chilika Lagoon, India." In *Coastal Ecosystems: Environmental Importance, Current Challenges and Conservation Measures*, 285–303. Springer International Publishing. https://doi.org/10.1007/978-3-030-84255-0_12.
- Acharyya, T., S. Raulo, S. Singh, et al. 2023. "Status and Conservation Challenges of the Second-Largest Seagrass Bed in India: Chilika Lagoon." *Environmental Science and Pollution Research* 30: 100265–100281. <https://doi.org/10.1007/s11356-023-29369-w>.
- Akadiri, S. A., P. O. Dada, A. A. Badejo, O. J. Adeosun, A. T. Ogunrinde, and O. T. Faloye. 2024. "Phytoremediation of an Integrated Poultry and Aquaculture Wastewater Using Sub-Surface Constructed Wetland Planted With *Phragmites karka* and *Typha latifolia*." *International Journal of Phytoremediation* 26: 1133–1143. <https://doi.org/10.1080/15226514.2023.2294485>.
- Akhter, N., M. Aqeel, M. K. Irshad, et al. 2024. "Differential Capacity of *Phragmites* Ecotypes in Remediation of Inorganic Contaminants in Coastal Ecosystems: Implications for Climate Change." *Environmental Research* 247: 118127. <https://doi.org/10.1016/j.envres.2024.118127>.
- Behera, P., M. Mohapatra, T. K. Adhya, M. Suar, A. K. Pattnaik, and G. Rastogi. 2018. "Structural and Metabolic Diversity of Rhizosphere Microbial Communities of *Phragmites karka* in a Tropical Coastal Lagoon." *Applied Soil Ecology* 125: 202–212. <https://doi.org/10.1016/j.apsoil.2017.12.023>.
- Bhatta, K., and H. K. Patra. 2020. "Economically Important Macrophytes of Chilika Lagoon, Odisha, India." *International Journal of Advanced Science and Technology* 29: 5131–5137.
- Bonanno, G., and M. Orlando-Bonaca. 2018. "Trace Elements in Mediterranean Seagrasses and Macroalgae. A Review." *Science of the Total Environment* 618: 1152–1159. <https://doi.org/10.1016/j.scitotenv.2017.09.192>.
- Carruthers, T. J. B., S. B. Jones, M. K. Terrell, et al. 2024. "Identifying and Filling Critical Knowledge Gaps Can Optimize Financial Viability of Blue Carbon Projects in Tidal Wetlands." *Frontiers in Environmental Science* 12: 1421850. <https://doi.org/10.3389/fenvs.2024.1421850>.
- Chambers, R. M., L. A. Meyerson, and K. Saltonstall. 1999. "Expansion of *Phragmites australis* Into Tidal Wetlands of North America." *Aquatic Botany* 64: 261–273. [https://doi.org/10.1016/S0304-3770\(99\)00055-8](https://doi.org/10.1016/S0304-3770(99)00055-8).
- Cunha, A. H., and C. M. Duarte. 2004. "Population Age Structure and Rhizome Growth of *Cymodocea nodosa* in the Ria Formosa (Southern Portugal)." *Marine Biology* 146: 841–847. <https://doi.org/10.1007/s00227-004-1496-2>.
- Duarte, C., N. Marbá, N. Agawin, et al. 1994. "Reconstruction of Seagrass Dynamics: Age Determinations and Associated Tools for the Seagrass Ecologist." *Marine Ecology Progress Series* 107: 195–209. <https://doi.org/10.3354/meps107195>.
- Finlayson, C. M., G. Rastogi, D. R. Mishra, and A. K. Pattnaik. 2020. *Ecology, Conservation, and Restoration of Chilika Lagoon, India*, 6. Springer. <https://doi.org/10.1007/978-3-030-33424-6>.
- Fouad, A. M. M., M. O. Arnous, M. S. Zaghloul, and A. A. Moustafa. 2025. "Expansion of *Phragmites australis* in Response to Climate Change and Human Activities in Wetland Ecosystems, Ismailia, Egypt." *Science Africa* 28: e02613. <https://doi.org/10.1016/j.sciaf.2025.e02613>.
- Fourqurean, J. W., N. Marbá, and C. M. Duarte. 2003. "Elucidating Seagrass Population Dynamics: Theory, Constraints, and Practice." *Limnology and Oceanography* 48: 2070–2074. <https://doi.org/10.4319/lo.2003.48.5.2070>.
- Ganguly, D., G. Singh, P. Ramachandran, A. P. Selvam, K. Banerjee, and R. Ramachandran. 2017. "Seagrass Metabolism and Carbon Dynamics in a Tropical Coastal Embayment." *Ambio* 46: 667–679. <https://doi.org/10.1007/s13280-017-0916-8>.
- Gibbs, J. P. 2000. "Wetland Loss and Biodiversity Conservation." *Conservation Biology* 14: 314–317. <https://doi.org/10.1046/j.1523-1739.2000.98608.x>.
- Hershner, C., and K. J. Havens. 2008. "Managing Invasive Aquatic Plants in a Changing System: Strategic Consideration of Ecosystem Services." *Conservation Biology* 22: 544–550. <https://doi.org/10.1111/j.1523-1739.2008.00957.x>.
- Howard, J., S. Hoyt, K. Isensee, M. Telszewski, and E. Pidgeon. 2014. "Coastal Blue Carbon: Methods for Assessing Carbon Stocks and Emissions Factors in Mangroves, Tidal Salt Marshes, and Seagrasses."
- Ilori, C. O., N. Pahlevan, and A. Knudby. 2019. "Analyzing Performances of Different Atmospheric Correction Techniques for Landsat 8: Application for Coastal Remote Sensing." *Remote Sensing* 11: 1–20. <https://doi.org/10.3390/rs11040469>.
- Lambin, E. F., and A. H. Strahler. 1994. "Change-Vector Analysis in Multitemporal Space: A Tool to Detect and Categorize Land-Cover Change Processes Using High Temporal-Resolution Satellite Data." *Remote Sensing of Environment* 48: 231–244. [https://doi.org/10.1016/0034-4257\(94\)90144-9](https://doi.org/10.1016/0034-4257(94)90144-9).
- Keller, R. P., A. Masoodi, and R. T. Shackleton. 2018. "The Impact of Invasive Aquatic Plants on Ecosystem Services and Human Well-Being in Wular Lake, India." *Regional Environmental Change* 18: 847–857. <https://doi.org/10.1007/s10113-017-1232-3>.
- Meyerson, L. A., K. Saltonstall, L. Windham, E. Kiviat, and S. Findlay. 2000. "A Comparison of *Phragmites australis* in Freshwater and Brackish Marsh Environments in North America." *Wetlands Ecology and Management* 8: 89–103. <https://doi.org/10.1023/a:1008432200133>.
- Mishra, A., and D. Apte. 2020. "Ecological Connectivity With Mangroves Influences Tropical Seagrass Population Longevity and Meadow Traits Within an Island Ecosystem." *Marine Ecology Progress Series* 644: 47–63. <https://doi.org/10.3354/meps13349>.
- Mishra, A. K., P. Acharya, D. Apte, and S. H. Farooq. 2023. "Seagrass Ecosystem Adjacent to Mangroves Store Higher Amount of Organic Carbon of Andaman and Nicobar Islands, Andaman Sea." *Marine*

- Pollution Bulletin* 193: 115135. <https://doi.org/10.1016/j.marpolbul.2023.115135>.
- Mishra, A. K., and S. H. Farooq. 2022a. "Trace Metal Accumulation in Seagrass and Saltmarsh Ecosystems of India: Comparative Assessment and Bioindicator Potential." *Marine Pollution Bulletin* 174: 113251. <https://doi.org/10.1016/j.marpolbul.2021.113251>.
- Mishra, A. K., and S. H. Farooq. 2022b. "Lack of Ecological Data Hinders Management of Ecologically Important Saltmarsh Ecosystems: A Case Study of Saltmarsh Plant *Porteresia coarctata* (Roxb.)." *Journal of Environmental Management* 321: 115957. <https://doi.org/10.1016/j.jenvman.2022.115957>.
- Mishra, A. K., and S. H. Farooq. 2025. "Short-Term Nitrogen Enrichment Induces Sulfide Intrusion in Tropical Oligotrophic Seagrass Meadows." *Rhizosphere* 35: 101128. <https://doi.org/10.1016/j.rhisph.2025.101128>.
- Mishra, A. K., M. K. Khadanga, S. Patro, D. Apte, and S. Hilal. 2021. "Population Structure of a Newly Recorded (*Halodule uninervis*) and Native Seagrass (*Halophila ovalis*) Species From an Intertidal Creek Ecosystem." *Lakes & Reservoirs: Research and Management* 26: 1–12. <https://doi.org/10.1111/lre.12376>.
- Mishra, A. K., C. Luong, C. Premarathne, et al. 2026. "Lack of Local Management and Limited Adaptive Capacity Are Pushing the Vulnerable Seagrass (*Halophila beccarii* Aschers.) Towards Extinction Across the Indo-Pacific." *Frontiers in Conservation Science* 7: 1734915. <https://doi.org/10.3389/fcsc.2026.1734915>.
- Mishra, A. K., A. Mishra, S. K. Mohakud, P. Acharya, P. R. Muduli, and S. H. Farooq. 2024. "COVID-19 Induced Lockdown Reduced Metal Concentration in the Surface Water and Bottom Sediment of Asia's Largest Lagoon." *Marine Pollution Bulletin* 209: 117127. <https://doi.org/10.1016/j.marpolbul.2024.117127>.
- Mishra, A. K., R. Rasheed, and S. H. Farooq. 2025. "Seagrass Population Dynamics and Biodiversity Assemblages Indicate Negative Effects of Short-Term Nutrient Enrichment in Tropical Island Ecosystem." *Journal of Environmental Management* 373: 123797. <https://doi.org/10.1016/j.jenvman.2024.123797>.
- Mishra, A. K., R. Santos, and J. M. Hall -Spencer. 2019. "Elevated Trace Elements in Sediments and Seagrasses at CO₂ Seeps." *Marine Environmental Research* 153: 104810. <https://doi.org/10.1016/j.marenvres.2019.104810>.
- Mishra, A. K., K. M. Watson, H. T. Ng, et al. 2025. "Seasonality and Local Nutrient Loading Drive Changes in Organic Carbon in Seagrass Ecosystems in Hong Kong." *Estuarine, Coastal and Shelf Science* 323: 109427. <https://doi.org/10.1016/j.ecss.2025.109427>.
- Misra, G., F. Cawkwell, and A. Wingler. 2020. "Status of Phenological Research Using Sentinel-2 Data: A Review." *Remote Sensing* 12: 10–14. <https://doi.org/10.3390/RS12172760>.
- Mohanty, S., P. C. Pandey, M. Pandey, P. K. Srivastava, and C. S. Dwivedi. 2024. "Wetlands Contribution and Linkage to Support SDGs, Its Indicators and Targets- A Critical Review." *Sustainable Development* 32: 5348–5392. <https://doi.org/10.1002/sd.2948>.
- Nabi, M. 2021. "Heavy Metals Accumulation in Aquatic Macrophytes From an Urban Lake in Kashmir Himalaya, India." *Environmental Nanotechnology, Monitoring & Management* 16: 100509. <https://doi.org/10.1016/j.enmm.2021.100509>.
- Nayak, S. S., S. Pradhan, D. Sahoo, and A. Parida. 2020. "De Novo Transcriptome Assembly and Analysis of *Phragmites karka*, an Invasive Halophyte, to Study the Mechanism of Salinity Stress Tolerance." *Scientific Reports* 10: 5192. <https://doi.org/10.1038/s41598-020-61857-8>.
- Nazneen, S., A. K. Mishra, N. J. Raju, and G. Mehmood. 2022. "Coastal Macrophytes as Bioindicators of Trace Metals in the Asia's Largest Lagoon Ecosystem." *Marine Pollution Bulletin* 178: 113576. <https://doi.org/10.1016/j.marpolbul.2022.113576>.
- Ogurcak, D. E., J. P. Sah, R. M. Price, and M. S. Ross. 2019. "Shifting Baselines in Coastal Forests: Rising Seas Transform Plant Communities From the 'Ground' up." *Forest Ecology and Management* 453: 117581. <https://doi.org/10.1016/j.foreco.2019.117581>.
- Panigrahi, S., B. C. Acharya, R. C. Panigrahy, B. K. Nayak, K. Banarjee, and S. K. Sarkar. 2007. "Anthropogenic Impact on Water Quality of Chilika Lagoon RAMSAR Site: A Statistical Approach." *Wetlands Ecology and Management* 15: 113–126. <https://doi.org/10.1007/s11273-006-9017-3>.
- Pérez-Ruzafa, A., C. Marcos, I. M. Pérez-Ruzafa, and M. Pérez-Marcos. 2011. "Coastal Lagoons: "Transitional Ecosystems" Between Transitional and Coastal Waters." *Journal of Coastal Conservation* 15: 369–392. <https://doi.org/10.1007/s11852-010-0095-2>.
- Piñeiro-Juncal, N., C. B. de los Santos, M. Dahl, et al. 2026. "Global Meta-Analysis Reveals Variability in Seagrass Carbon Storage, Pollution Mitigation and Benthic Biodiversity Enhancement Provisioning." *Ecosystems* 29: 62. <https://doi.org/10.1007/s10021-026-01090-y>.
- Sahu, B. K., P. Pati, and R. C. Panigrahy. 2014. "Environmental Conditions of Chilika Lake During Pre and Post Hydrological Intervention: An Overview." *Journal of Coastal Conservation* 18: 285–297. <https://doi.org/10.1007/s11852-014-0318-z>.
- Sarkar, S., U. K. Sarkar, S. Ali, S. Kumari, and M. Puthiyotti. 2021. "Status, Ecological Services and Management of Aquatic Weeds of Floodplain Wetlands in India: An Overview." *Lakes & Reservoirs: Science, Policy and Management for Sustainable Use* 26: 76–91. <https://doi.org/10.1111/lre.12353>.
- Sasmito, S. D., A. K. Mishra, C. Duvert, et al. 2026. "Contrasting Sediment and Aquatic CO₂ and CH₄ Effluxes Across Australian Tropical Salt Flat, Saltmarsh, Mangrove and Tidally Restricted Wetlands." *Estuarine, Coastal and Shelf Science* 330: 109693. <https://doi.org/10.1016/j.ecss.2025.109693>.
- Srichandan, S., J. Y. Kim, A. Kumar, et al. 2015. "Interannual and Cyclone-Driven Variability in Phytoplankton Communities of a Tropical Coastal Lagoon." *Marine Pollution Bulletin* 101: 39–52. <https://doi.org/10.1016/j.marpolbul.2015.11.030>.
- Swain, P. R., P. K. Parida, P. Panikkar, B. K. Behera, S. K. Nag, and B. K. Das. 2022. "Impact Assessment of an Invasive Macrophyte Community on Ecosystem Properties: A Mass Balance Approach for Chilika Lagoon, India." *Ecological Informatics* 69: 101592. <https://doi.org/10.1016/j.ecoinf.2022.101592>.
- Teixeira Pinto, C., X. Jing, and L. Leigh. 2020. "Evaluation Analysis of Landsat Level-1 and Level-2 Data Products Using In Situ Measurements." *Remote Sensing* 12, no. 16: 2597. <https://doi.org/10.3390/RS12162597>.
- Theuerkauf, S. J., B. J. Puckett, K. W. Theuerkauf, E. J. Theuerkauf, and D. B. Eggleston. 2017. "Density-Dependent Role of an Invasive Marsh Grass, *Phragmites australis*, on Ecosystem Service Provision." *PLoS ONE* 12: 1–16. <https://doi.org/10.1371/journal.pone.0173007>.
- Wails, C. N., K. Baker, R. Blackburn, et al. 2021. "Assessing Changes to Ecosystem Structure and Function Following Invasion by *Spartina alterniflora* and *Phragmites australis*: A Meta-Analysis." *Biological Invasions* 23: 2695–2709. <https://doi.org/10.1007/s10530-021-02540-5>.
- Windham, L., J. S. Weis, and P. Weis. 2003. "Uptake and Distribution of Metals in Two Dominant Salt Marsh Macrophytes, *Spartina alterniflora* (Cordgrass) and *Phragmites australis* (Common Reed)." *Estuarine, Coastal and Shelf Science* 56: 63–72. [https://doi.org/10.1016/S0272-7714\(02\)00121-X](https://doi.org/10.1016/S0272-7714(02)00121-X).
- Wu, C., D. Peng, K. Soudani, et al. 2017. "Land Surface Phenology Derived From Normalized Difference Vegetation Index (NDVI) at Global FLUXNET Sites." *Agricultural and Forest Meteorology* 233: 171–182. <https://doi.org/10.1016/j.agrformet.2016.11.193>.

Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** Sample maps used for the extent mapping of *Phragmites karka* for the year 2025. **Figure S2:** Plot showing *P. karka* extent variation and its associated changes in relation to salinity in last 35 years in the Chilika lagoon, India. **Table S1:** Temporal variation of *P. karka* extent in the northern sector of the Chilika lagoon with respect to various natural extreme events and man-made changes. **Table S2:** Results of one-way ANOVA of physical parameters of the water samples presented in Table 1. **Table S3:** Results of one-way ANOVA of physical parameters of the sediments samples presented in Table 2. **Table S4:** Mean $\pm$ standard deviation (SD) and (min-max) of trace-metal concentrations presented in Figure 4. FR = Floating root. **Table S5:** Range of BSAF values presented in Figure 5. **Table S6A:** Data for supporting the Figure 6 on age frequency distribution of *P. karka*. **Table S6B:** Mean $\pm$ SD of R = long-term average recruitment, Ro = present recruitment, r = growth rate. SD values are not available for Ro and R and shoot longevity.