

Research Article

Invasive aquatic floating plants are naturalizing in the Yucatán Peninsula, México

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Citation: Huix CM, Cohuo S, León HJO, Soto EG, Hernández PH, Leary JJK (2025) Invasive aquatic floating plants are naturalizing in the Yucatán Peninsula, México. *BioInvasions Records* 14(4): 857–870, <https://doi.org/10.3391/bir.2025.14.4.09>

Received: 21 October 2024

Accepted: 5 June 2025

Published: 26 September 2025

Handling editor: Stelios Katsanevakis

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Abstract

The Yucatan Peninsula (YP) is a unique hydrological region, characterized by a broad range of freshwater environments, most of them oligotrophic and interconnected by karstic subterranean channels, without surficial connections. Urban expansion and tourism over the last several decades have led to increased eutrophication of this aquatic system. For over a century, the invasive floating plants (FP) water lettuce (*Pistia stratiotes* L.) and water hyacinth (*Pontederia crassipes* [Mart.]) have become naturalized in many eutrophic waterbodies throughout México and Central America. La Sabana is a small (109 ha), peri-urban lake near the coastal city of Chetumal in the state of Quintana Roo that has recently shifted from a mesotrophic to hypereutrophic state due to municipal wastewater discharges. Starting in 2017, coincident invasions of both species survived and reproduced into monospecific infestations in La Sabana. A supervised classification and analysis of satellite imagery measured significant expansions (M-K test $z = 6.13$) of water lettuce peaking to 24.7 ha in 2021 and water hyacinth peaking to 18.9 ha in 2023. According to historical surveys, detection of these FP in the YP goes back decades, but here is a first report of FP populations in the YP naturalizing into perpetuating colonies. Eutrophication of YP freshwater systems is likely increasing the suitability for FP to establish and thrive. While a lack of surficial connections is impeding natural hydrochory, increasing human visitation (e.g., tourism) will increase the risk of stochastic introduction. This study describes the naturalizing process of FP in La Sabana and is an early warning of potential vulnerabilities to the rest of the waterbodies in the YP to FP naturalizations that could have irreversible consequences with environmental quality, ecological disruption, and future economic burdens.

Key words: naturalization, remote sensing, *Pistia stratiotes*, *Pontederia crassipes*, Lake La Sabana

Introduction

The Yucatán Peninsula (YP) is a flat, karstic landscape in the tropics of southern México with a unique hydrology that is characterized by large, subterranean conduits interconnecting a variety of surficial lakes, cenotes (freshwater dolines) and aguadas (semi-permanent pools) that support a wide diversity of groundwater-dependent ecosystems (Bauer-Gottwein et al. 2011; Angyal et al. 2022). The geology of the aquifer consists of limestones, dolomites, and evaporites, making most surficial waters calcitic with high

concentrations of sulfates (SO_4^{2-}), calcium (Ca^{2+}) and magnesium (Mg^{2+}) (Macario-González et al. 2022). These calcite-rich aquatic environments commonly co-precipitate with phosphates or orthophosphates creating oligo-mesotrophic conditions that are particularly unsuitable to non-native floating plants (FP) (Camargo-Guerra et al. 2013; Macario-González et al. 2022).

Over the last 30 years, economic growth and urban expansion across the YP is measurably altering the limnology of these oligotrophic systems with point and non-point sources of heavy metals (Ortega-Camacho et al. 2023), agrochemicals (Polanco Rodríguez et al. 2015), medicaments (Metcalfe et al. 2011), and nutrients (Derrien et al. 2015). Aquatic environments located near urban centers have been especially altered by point source discharges of wastewater causing eutrophication (Tobón Velázquez et al. 2019).

Lake La Sabana is a small, peri-urban lake on the edge of the small, but densely populated, coastal city of Chetumal (pop. > 233,648). It has been significantly modified with impoundments separating the larger pool from the contiguous smaller pools and wetlands. The larger pool has been receiving point source discharges of partially treated wastewater since 1999 (Alpuche 2014; Cohuo et al. 2023). As a result, the trophic state of La Sabana has progressively changed from mesotrophic to hypereutrophic with total phosphorous levels measured in excess of $190 \mu\text{g L}^{-1}$ (Cohuo et al. 2023).

Invasions of water lettuce (*Pistia stratiotes* L.) and water hyacinth (*Pontederia crassipes* [Mart.]) in México date back to the late 19th century and are coincident with man-made impoundments (Alfaro et al. 2021; Martínez Jiménez and Gómez Balandra 2022), creating eutrophic conditions promoting the competitive fitness of these species (Agami and Reddy 1990; Coetzee and Hill 2011). In particular, Gutiérrez et al. (1996) reported water hyacinth to infest over 64% of México's impounded waters (> 40,000 ha). Naturalized FP grow into large monospecific colonies disrupting shared community niche spaces by cutting off light to the photic zone, reducing dissolved oxygen and perpetuating autochthonous nutrient loading, which ultimately leads to degradations of water quality, faunal habitat and other complex ecosystem services (Mooney and Cleland 2001).

Richardson et al. (2000) defined naturalization as the stage where an introduced species overcomes biotic and abiotic barriers to survival and reproductive competence. It is this stage that is also synonymous with the lag phase of a sigmoidal invasion curve (Sakai et al. 2001). A recent survey of aquatic macrophytes in México by Martínez Jiménez and Gómez Balandra (2022) found water hyacinth to be the most common species. In fact, past surveys have vouchered both species in the three states that make up the YP (i.e., Campeche, Yucatan, and Quintana Roo) (Bonilla-Barbosa and Maria Araúz 2014). In 2017, a monospecific colony of water lettuce was detected in La Sabana (Cohuo et al. 2020), followed by another successful colony of water hyacinth detected in 2021. To our knowledge,

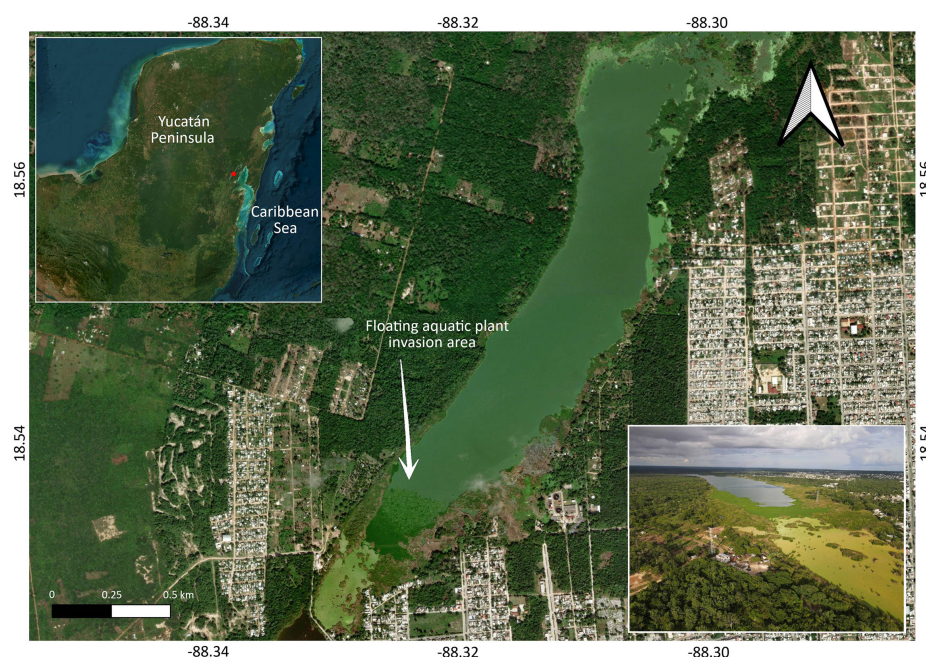


Figure 1. Lake La Sabana in the City of Chetumal is located on the shore of Chetumal Bay ca. 2021. Inlay (bottom, right) shows oblique north-facing viewshed. Water lettuce and water hyacinth are in the foreground and background, respectively.

this is the first report of these two species naturalizing within the YP. In this study, we describe: (i) the rate of expansion of these two populations with remote sensing satellite imagery; (ii) the prevalence of these species detected and vouchered throughout the YP; and (iii) steps to mitigate these invasions.

Materials and methods

Study area

The climate of southern YP is warm and sub-humid (Quej et al. 2016) with a regional average temperature of 26 °C and mean annual rainfall of 1300 mm (Cálix de Dios 2014). La Sabana (18.5141°N, 88.3038°W) is a shallow, elongated lake partitioned into four sub-basins with dams impeding surficial exchange (Figure 1). The largest north sub-basin is 109 ha and has been the recipient of daily point source discharges of partially treated wastewater since 1999, as described by Cohuo et al. (2023).

Estimating FP coverage in Lake La Sabana with satellite imagery

Atmospheric-corrected (Level 2a), true-color [red (665 nm) green (560 nm) and blue (490 nm)] composite imagery were collected from Copernicus Sentinel-2 Earth Observation satellite constellation and downloaded from the Sentinel Hub EO Browser (<https://apps.sentinel-hub.com/eo-browser/>, Sinergise Ltd.) on cloud-free dates from Oct 2017 to Nov 2023 (n = 57). Image raster files (.tif) were imported into QGIS (v. 3.16.14) and extracted from a vector boundary of the north sub-basin. The Semi-Automatic Supervised Classification plug-in (Congedo 2021) applying the Maximum

Likelihood algorithm was used to classify features for water lettuce, water hyacinth, littoral vegetation and open water from each image raster in the time series. A total of twelve training sites, each consisting of 10 contiguous pixels (e.g., 5×2), were created for each classifier from imagery captured on 12/25/2021. Training sites were selected in areas where coverage was clearly identifiable using available image sources (Rwanga and Ndambuki 2017), including high-resolution ortho-mosaic, Google Earth, and Sentinel-2 images, all integrated with field surveys. Pixel selection was primarily focused on the center of the coverages to avoid mixed pixels. The total pixel count of the study area was 9,101 pixels, with training sites representing 5.3% of the study area. To assess how spectrally distinct each land cover class was from the others, a class separability analysis was conducted using the Bray-Curtis Similarity (%) metric. This was calculated using mean reflectance values for each class (water lettuce, water hyacinth, littoral vegetation, and open water). Features were validated by a co-registered, ortho-mosaic of images captured on 06/12/2021, at 2 cm pixel resolution, with a Mavic Zoom 2 (SZ DJI Technology Co., Ltd.; Shenzhen, China) unoccupied aerial system outfitted with a 2.5-cm RGB electro-optical sensor with 20 million effective pixels. An accuracy assessment of the classifiers was performed with time-adjacent imagery from 11/25/2021 and 12/25/2021, using the AcATaMa plug-in (Kamusoko 2022) in QGIS with a random sample of pixels ($n = 60$), for each feature class scored manually as positive, type 1 or type 2 errors, which were then compiled into a confusion matrix to calculate user, producer and overall accuracies (Esaid et al. 2018). The F1 score was calculated based on user's accuracy (precision) and producer's accuracy (recall), following the approach outlined by Chicco and Jurman (2020).

Coverage was calculated for each FP class in the time series and subjected to a non-parametric Mann-Kendall test to measure trends of coverage over the monthly time series from 2017–2023 (Alencar da Silva and Silva 2017). These analyses were performed with the Paleontological Statistics software v. 4.08 (Hammer and Harper 2001).

Voucher surveys mapping FP distribution in the YP

Curated records of water lettuce ($n = 103$ points) and water hyacinth ($n = 189$ points) in the YP were acquired from the Mexican National Biodiversity Information System (SNIB) including records from the more recent crowd-sourced citizen scientist program iNaturalist (<https://enciclopedia.mx/especies>; accessed July 6, 2024). These vouchers were compiled from various sources. There were no protocols for how surveys were conducted. Thus, we assumed that most or all detections were opportunistic with possible biases in space and time due to the passive nature of the surveyor. Otherwise, we are confident of the correct identification of these vouchered species, including

Table 1. Confusion Matrix with User's Accuracy, Producer's Accuracy, and F1 Score for each Class

	Validation				Total	User's accuracy	Producer's accuracy	F1 Score	Overall accuracy
	Water Lettuce	Water Hyacinth	Littoral Vegetation	Water					
Water Lettuce	15	0	0	0	15	1	1	1	0.97
Water Hyacinth	0	15	0	0	15	1	1	1	
Littoral Vegetation	0	0	8	2	10	0.8	1	0.89	0.99
Water	0	0	0	20	20	1	0.97	0.99	
Total	15	15	8	22	60				

when and where they were collected. Beyond these vouchers we are unaware of any other comprehensive vegetation surveys mapping the YP. All data were downloaded as comma separated value files (.csv) with coordinate attributes referenced in World Geodetic System 1984 (WGS84).

Spatial relationships between vouchered locations with waterbodies and roads

Line vector data of the road network confined to the YP (n = 155,977 segments) were downloaded from the Humanitarian OpenStreetMap Team (<http://export.hotosm.org>; accessed July 6, 2024). Polygon vector data of freshwater features in the YP (n = 5074 features) were obtained from the Mexican National Institute of Statistics and Geography (INEGI) database (<https://en.www.inegi.org.mx>). Shortest Euclidian distances were calculated from Cartesian coordinates for all species voucher points and the nearest vertex of each freshwater feature polygon from the road network using the "Shortest line between features" tool in QGIS.

Results

A supervised classification was able to discriminate water lettuce and water hyacinth classes with both producer and user accuracies of 100%, and an overall classification accuracy of 97.76% (Table 1). This high level of accuracy allowed us to confidently detect and monitor changes in coverage between the two species over time. The Bray-Curtis similarity (%) metric indicated that *littoral vegetation* and *water* exhibited the highest spectral similarity (86.09%), closely followed by *Pistia* and *Pontederia* (85.51%), and *Pistia* and *littoral vegetation* (84.23%). The similarity between *Pontederia* and *littoral vegetation* was also relatively high (79.54%). In contrast, lower similarity values were observed between *Pistia* and *water* (70.96%), and between *Pontederia* and *water* (69.42%), suggesting greater spectral distinction between these vegetation types and open water.

Water lettuce was first detectable from satellite in October 2017 and reached 0.8 ha by December (Figure 2). The infestation continued to expand to 6.9 ha in 2018, 17.3 ha in 2019, 18.4 ha in 2020 and peaked to 24.7 ha in 2021 before dramatically dropping down to 3.4 ha in 2022 and 2.9 ha in 2023. Water hyacinth was first observed in the spring of 2021, as

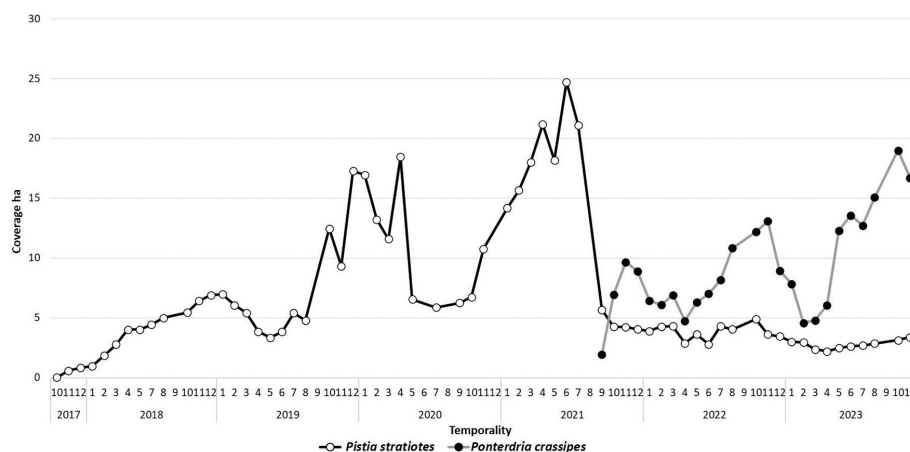


Figure 2. FAP coverage (ha) in Lake La Sabana from 2017–2023.

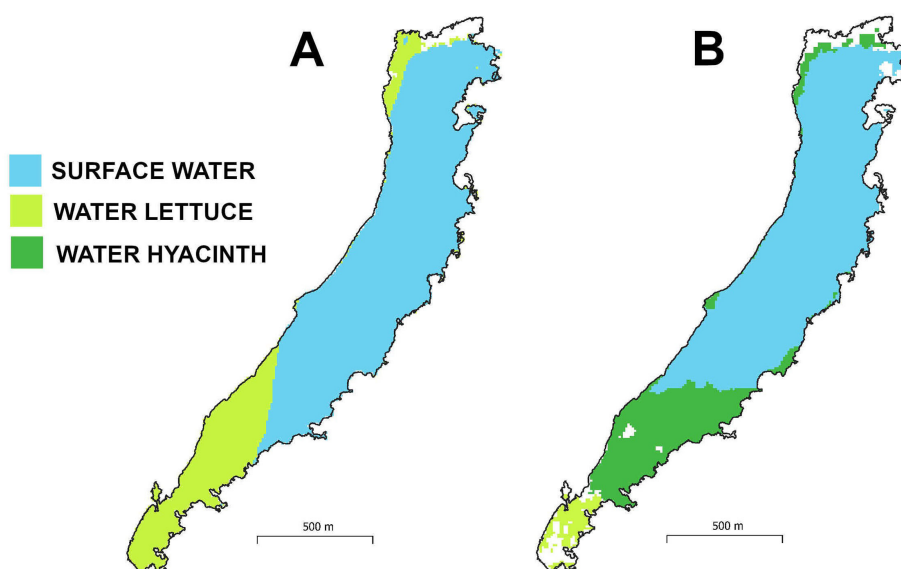


Figure 3. FAP coverages in La Sabana on 07/08/2021 (A) and 10/21/2023 (B) shifting from lettuce to hyacinth dominance.

small patches mixed with water lettuce (*personal observation*), while detection from satellite imagery was not until September 2021 with a 1.9 ha delimited patch that quickly expanded to 9.7 ha in November with continued expansions to 13.1 ha and 18.9 ha in 2022 and 2023, respectively (Figure 3). A Mann-Kendall test measured a significant positive trend ($Z = 6.13$; $P = 8.72e^{-10}$) for coverage expansion of both FP from 2017–2023 as evidence of both populations naturalizing in La Sabana.

Earliest SNIB records of water lettuce and water hyacinth date back to the early twentieth century. The first record of water lettuce in the YP was 1932 in Campeche, while it wasn't until 1981 when the first record of water hyacinth was made, again in Campeche. Records from iNaturalist dating back to 2009 totaled 107 water lettuce and 119 water hyacinth with non-linear increases in detections over time and the highest numbers recorded in 2023 (Figures 4, 5A). The average number of water lettuce records in the YP was greater than the average for the rest of the states, while the average

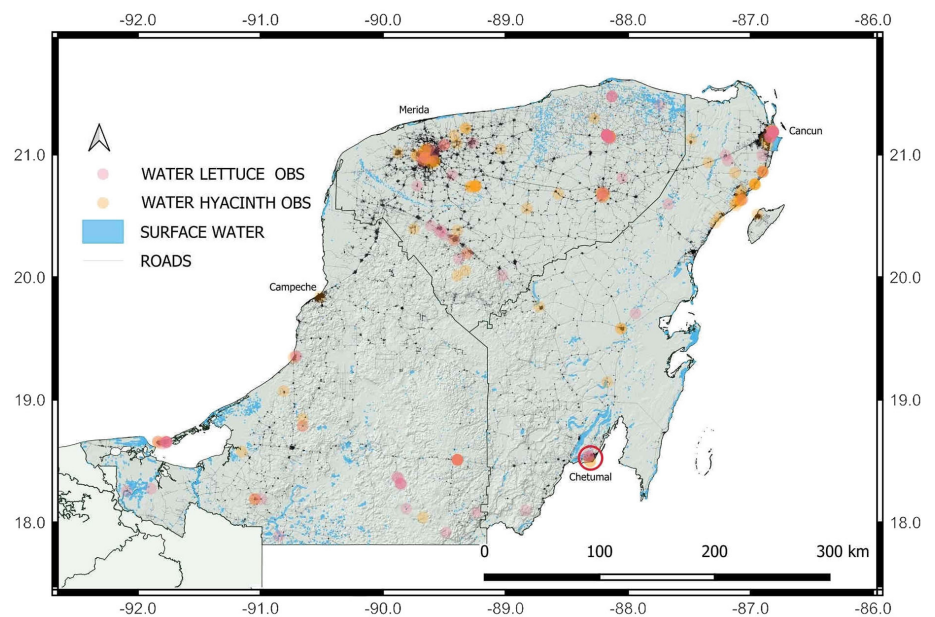


Figure 4. Map of the Yucatan Peninsula (YP) showing vouchered points from iNaturalist records from 2009 to 2023 for water hyacinth (orange) and water lettuce (pink).

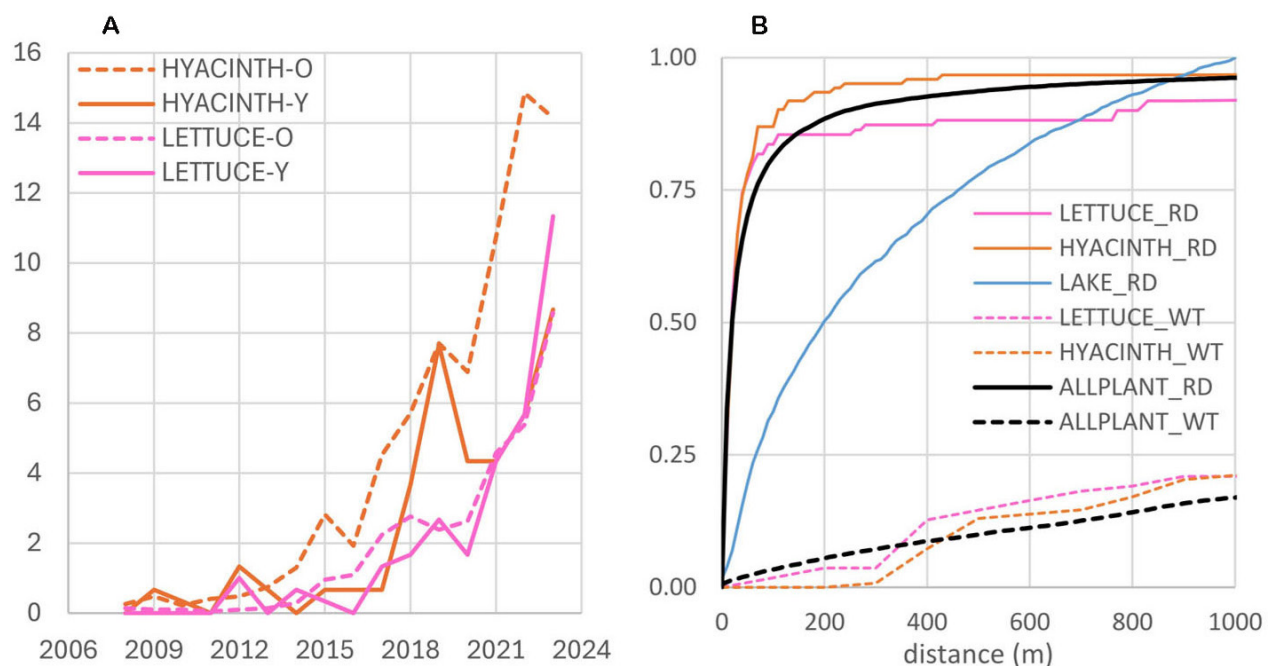


Figure 5. Water hyacinth (orange) and water lettuce (pink) records (A) Yucatan Peninsula (Y) and all other states (O); (B) cumulative density functions for water hyacinth and water lettuce distances from Roads (R) and water bodies (WT).

number of records for water hyacinth in the YP was much lower than the other states. The increasing number of detections over time is likely due to both the adoption success of the crowd sourcing technology and an actual increase in incidences, but we are unable to discern that here.

Distances of iNaturalist FP records were vastly different between roads and waterbodies (Figure 5B). Median distances of water lettuce and water hyacinth were 19 and 20 m from the nearest road, while average distances to the nearest water body were 3414 and 3309 m, respectively. Moreover,

88% of water lettuce records were < 500 m from a road while 86% were > 500 m from a waterbody. Similarly, 96% of water hyacinth records were < 500 m from a road while 88% were > 500 m from a waterbody. Finally, the median distance of waterbodies from roads was 198 m, with 77% of waterbodies < 500 m of a road. This strong segregation of FP records between roads and waterbodies may be the combined influence of opportunistic surveys, to be expected from citizen scientists, and also a likely condition of stochastic dispersal confined to more accessible areas along the road with small water features.

Discussion

In the era of globalization, the transport of international commerce has greatly accelerated non-native species introductions to novel locations beyond their natural ranges (Meyerson and Mooney 2007). However, the introduction of a non-native species alone does not qualify it as an invasive species. Many non-native introductions may not overcome the biotic and abiotic factors of a novel environment leading to local extinctions mitigating invasions at the point of introduction (Blackburn et al. 2011). Other species may eventually overcome these barriers with an extended lag “establishment” phase involving multiple stochastic introductions and extinctions, eventually resulting in survivors reproducing and subsequent generations growing exponentially into incipient populations. The term of that lag phase can vary widely and depend on outside propagule pressures influencing introduction rates and habitat suitability influencing survivorship (Reddy and DeBusk 1984; Sakai et al. 2001; Chen et al. 2014). Kleinschroth et al. (2021) found many water hyacinth invasions had substantially long, decadal lag phases with extreme fluctuations in coverage and some populations crashing. Extreme fluctuations in FP coverage was observed in La Sabana and seems to be consistent with the observations of a lag phase described here. While our first report of FP on La Sabana was in 2017, it is possible that there have been several previous introductions influenced by persistently large propagule pressures from neighboring states but seemingly didn’t survive at the point of introduction.

Shifts in species dominance on La Sabana were apparent, switching from water lettuce to water hyacinth. Water hyacinth has been shown to outcompete water lettuce for light and nutrients in controlled mesocosms and natural systems (Agami and Reddy 1990; Shekede et al. 2008). Reddy and Debusk (1984) showed densities of water hyacinth reaching up to 2 kg dry wt/m², compared to water lettuce densities only reaching up to 1 kg dry wt/m². A quadrat sampling survey between September–November 2021 measured water hyacinth and water lettuce dry weight densities on La Sabana to be 1.2 ± 0.3 kg/m² and 0.6 ± 0.2 kg/m², respectively (Huix 2022). These are consistent with densities measured in novel (Africa) and native

(South America) home ranges (Shekede et al. 2008; Struik et al. 2022) and are within the range of “operational densities”, described by Agami and Reddy (1990), approaching potential growth maxima in suitable habitats.

Both FP are native to tropical regions of South America and adapted to the mild temperatures (e.g., 25–30 °C) observed in much of Mexico (Wilson et al. 2000; Thayer et al. 2018). Beyond tropical temperatures and a hydric environment, phosphorous (P) is also considered a limiting factor to growth and survival for both species (Soti and Volin 2010; Güereña et al. 2015). Reddy et al. (1990) measured survival and growth of water hyacinth in solution with total P exceeding 10 mg/L, while Shardendu et al. (2012) showed even higher tolerance with water lettuce surviving in total P exceeding 50 mg/L. Optimal growth for water hyacinth has been measured in solutions at 1 mg/L total P (Reddy et al. 1990), but apparently may also survive in P concentrations as low as 0.01 mg/L (Kobayashi et al. 2008). All of these studies were performed in controlled mesocosms for short term responses. It is not completely understood how FP would behave under these same conditions in a natural environment under longer term. The concentration of 0.19 mg/L P in La Sabana makes the system hypereutrophic and was high enough to support naturalization of both FP. We assume that lower P levels in La Sabana would still support naturalization while increasing levels would accelerate population expansion.

Herrera et al. (1998) surveyed 71 water bodies across the YP and found all of them to be P limited due to calcite saturated systems with a strong affinity to coprecipitate with phosphorus. At the time, 67% of those water bodies were oligotrophic with P levels at less than 0.015 mg/L, while 15% were eutrophic with P levels ranging from 0.09–0.62 mg/L, which were characterized as lentic systems found adjacent to urban centers and agricultural production (Herrera et al. 1998, Schmitter-Soto et al. 2002). Vegetation surveys of these cenotes identified a number of emergent and submersed macrophyte species but noticeably did not identify water lettuce nor water hyacinth (Schmitter-Soto et al. 2002). While some research suggests survivorship in very low levels of phosphorus, it is plausible that most of the oligotrophic systems in the YP may not be suitable for supporting FP. However, it is also apparent that there are several water bodies with high enough nutrient levels to support FP naturalization. Most of the water bodies of the YP are groundwater dependent, which is increasingly being impacted by anthropogenic eutrophication from non-point sources (Bauer-Gottwein et al. 2011), which may eventually instigate the proliferation of introduced FP.

Both FP have similar sexual and asexual reproduction strategies. They both sexually reproduce seeds that sink to the bottom of the water column and germinate in shallow, littoral areas exposed to high light (Dray and Center 1989). While an important life history trait, it is considered secondary to clonal offset (i.e., ramet) production (Dray and Center 1989). Moreover,

cenotes can be quite deep and often lacking littoral shelves, making them generally not conducive habitat for seed germination. Ramets and seedlings for both FP produce aerial parts that are buoyant and evolved to passively disperse via hydrochory. However, the YP lacks topographical relief leaving most of the water bodies in the YP disconnected from a surficial drainage network. Hence a natural barrier to FP dispersal.

Tourism and outdoor recreation (e.g., ecotourism) are considered primary pathways to assisted colonization of invasive species (Anderson et al. 2015; Hulme 2015). Tourism in the YP started to dramatically increase in the 1980s and has become an important economic engine for the region and country (Lebedeva et al. 2017). In part, government programs have certified over 100 cenotes as attractions for recreation (Arcega-Cabrera et al. 2023). In 2023, Cancun (Quintana Roo) registered 10 M airport arrivals, making it the most visited place in Latin America (SECTUR 2023). Increasing tourist activities at these freshwater systems increases point source pollution leading to eutrophication (Arcega-Cabrera et al. 2023) and the risk of introducing FP (Choi et al. 2023). However, the FP introduction by animal movements across landscapes or hydrological regions (Holm 1977) e.g., Central America or Southern México to YP can be still a possibility to assist colonization, particularly during seasonal bird migration in which seeds can be passively transported, but this remain to be proved.

In this study, we illustrate the strong association of FP detections with the road network. Urban expansion, such as what has been experienced in the YP over the last several decades, leads to concomitant increases in population and infrastructural developments in overland transportation. An increase in mobility leads to humans becoming vectors for stochastic long-distance dispersal of invasive species (Lukács and Valkó 2021; Lemke et al. 2019), including aquatic invasive species (Johnson et al. 2001). In one study it was found to be the primary pathway of aquatic species invasions over natural dispersal and suitable habitat conditions (Kinsley et al. 2024). Being that FP are conspicuous propagules, it seems implausible that dispersal would be passively carried out by a person visiting freshwater systems within the YP. However, with a lack of awareness of their invasive status and ecological impact, it becomes more plausible that people could be more deliberate vectors to introducing FP into these aquatic systems either due to an aesthetic attraction to the species (e.g., flower) or thinking it may be native to the ecosystem (Hulme 2015).

As shown in La Sabana, small FP populations quickly grow into large surface mats that can dramatically modify the ecosystem. The measured impacts of light reduction, biodiversity loss and biogeochemical change are potentially irreversible (Alfaro et al. 2021; Karouach et al. 2022). In México, water hyacinth incurs the greatest costs to unprotected aquatic ecosystems (Rico-Sánchez et al. 2021). In the YP, infestations of cenotes would mitigate light penetration through the water column, competitively excluding other macrophyte and planktonic community members. Surface mats slough large

detrital loads contributing to organic matter sedimentation which can increase sulfide production to undesirable levels (Stoessel et al. 1993). Inherently, FP infestations would render cenotes a health risk and unusable for recreation. Management would be exceptionally difficult due to the limited access of these systems. Moreover, herbicides are the most conventional approach to effective management, but would be highly unpopular for use in these natural heritage sites.

Conclusions

Lake La Sabana has undergone significant anthropogenic eutrophication over the last two decades creating an environment conducive to FP naturalization. As tourism and urbanization continue to thrive in the YP, we see other freshwater systems within this hydrological system succumbing to anthropogenic eutrophication, increasing the risk to novel FP colonization. Lake La Sabana should serve as a warning to this existential threat. Holistically, regional-scale nutrient reduction plans preserving the oligotrophic nature of these fragile aquatic systems will serve as the ultimate prophylactic against FP populations naturalizing in the YP. Moreover, educational programs should be established to bring awareness to locals and visitors recreating at the cenotes so that they are aware of these species along with the potential risks with being found in these systems.

Authors' contribution

All authors contributed to research conceptualization, sample design and methodology, investigation and data collection, data analysis and interpretation, ethics approval, funding provision, original draft writing, review and editing.

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Acknowledgements

The authors of this research acknowledge Franklin Martínez, Juan Ayuso, Miguel Aragon, and Celeste Ventura for their assistance in the field and laboratory analyses, and we gratefully recognize the insightful comments and valuable suggestions provided by the reviewers, which greatly enhanced the clarity and rigor of this manuscript.

Funding declaration

Tecnológico Nacional de México (TecNM) project number 22806.25-P and the Secretaría de Ciencia, Humanidades, Tecnología e Innovación (SECIHTI) with fellowship number 1081802 supported this study. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

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