



Detection of an invasive plant (*Cissus verticillata*) in the largest mangrove system on the eastern Pacific coast—a remote sensing approach

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Abstract The identification and monitoring of invasive plant species utilizing spaceborne sensors have posed substantial challenges over the past few decades, mainly due to a scarcity of state-of-the-art sensors, limited digital processing capabilities, and the presence of a phenological spectral feature that is not readily detectable by conventional methods. The invasive plant *Cissus verticillata*, first detected

in 2017, has affected the largest mangrove system on the eastern Pacific coast—Marismas Nacionales—spreading rapidly and aggressively through the mangrove canopy, and causing degradation and even mortality, mainly of *Rhizophora mangle*, by obstructing the sunlight over the canopy. The purpose of this study was to isolate the multispectral signal from *Cissus verticillata* by using a cloud computing approach with Google Earth Engine and generate a comprehensive map of the entire mangrove system by means of a novel dense time series of Sentinel-2 data. Results indicate that the optimal period for detecting *Cissus verticillata* is between October and December. Furthermore, this species is expanding its range along the riverbanks in the central region of Marismas Nacionales, with its coverage increasing from 426.16 ha in 2019 to 838.08 ha in 2021. These areas were verified with a field endeavor and have signified a substantial development, given that the plant had not been previously identified in this region with conventional field methods due to logistical constraints. The findings and approach of this study will contribute to the decision-making required to manage this invasive plant.

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Introduction

Invasive species are among the most important threats to biodiversity. They cost the global economy billions of dollars every year (Diagne et al. 2021). The introduction of non-native plant species outside of their native range is commonly a result of human activities, such as urbanization, aquaculture, and commerce (Hulme et al. 2023). Invasive plants can alter soil composition, disrupt natural ecological processes, and degrade habitats, ultimately reducing biodiversity and ecosystem resilience (Vilà et al. 2011). In coastal ecosystems, invasive plants can be particularly harmful as they can have detrimental effects on mangrove trees by competing for essential resources (Zhou et al. 2015), such as nutrients, light, and space (Biswas et al. 2018).

Given the impacts of invasive plant species on biodiversity and ecosystem processes (Bellard et al. 2016), the urgency of early detection and rapid response mechanisms has become of utmost importance. Indeed, prompt recognition endeavors are not just essential for identifying new invasive plant species (Seebens et al. 2017), but are also the key to pertinent decision-making related to the management and control of these species (Delgado et al. 2016). In this case, creating detailed maps with an adequate spatial resolution (m/pixel) is an important endeavor to accurately document the actual spread of plant invasions (Hill et al. 2017). When dealing with large areas, however, relying solely on field surveys to create complete maps is often impractical and time-consuming (Bradley 2014), particularly in coastal wetlands where muddy soils cause serious difficulties for field surveys (Flores-de-Santiago and Flores-Verdugo 2024). This is where the effectiveness and convenience of spaceborne technology become critical, offering a feasible solution for large-scale mapping (Valderrama-Landeros et al. 2024a).

While traditional detection and mapping of invasive plants rely on spectral differentiation among thematic classes, recent studies have introduced innovative approaches in remote sensing, such as the use of texture elements (Hill et al. 2017) and phenology-based methods (Celis-Hernandez et al. 2022). The latter, for instance, involves analyzing dense time series of remote sensing data based on vegetation indices to detect seasonal changes in plant growth stages. By understanding the specific

conditions of certain plant life cycles, it is possible to identify the most effective periods when invasive plants thrive in a particular region, which consequently facilitates the detection and mapping of such species (Bradley 2014; Valderrama-Landeros et al. 2021).

Cissus verticillata, commonly known as possum grape vine, is a climbing plant globally sought after for its ornamental allure and medicinal applications, with a wide native distribution in the Americas, ranging from Mexico to Argentina (Rojas-Sandoval 2022). Resorting to coiled tendrils for climbing or scrambling along the ground, *Cissus verticillata* displays remarkable regenerative abilities, readily sprouting aerial roots from pruned branches (Acevedo-Rodríguez and Strong 2012). Its propagation probably involves both seeds and vegetative means, with birds playing a role in dispersing its fleshy fruits (French et al. 2003; Smith 2010). This fast-growing plant forms dense canopies, depriving native understory plants of sunlight, which leads to the demise of host trees (Drobnik and De Oliveira 2015). Even though *Cissus verticillata* is considered native to a region of Mexico, it is not native to coastal ecosystems, as it is a freshwater plant (Rojas-Sandoval 2022). However, due to its high upwards expansion on mangrove trees, it does not touch salty water (French et al. 2003). It can thus be considered non-native in these coastal ecosystems and even invasive since it is already established and causing detrimental effects on native flora (Blackburn et al. 2011).

Cissus verticillata has been reported to negatively affect various tree species, such as live oak, black willow, and papaya, by smothering them with foliage (French et al. 2003). However, its impact on mangroves has not been reported in published literature. Given its aggressive behavior and potential ecological consequences on ecosystems that provide key services, studying its distribution and potential effects has become paramount. The aim of this research was, therefore, to assess the feasibility of using a dense time series of multispectral spaceborne data to detect *Cissus verticillata* on the largest mangrove system of the eastern Pacific coast. The results may yield reliable information for future national monitoring and eradication programs. The working hypothesis was that the detection of *Cissus verticillata* would depend directly on the season in which the spaceborne data were obtained.

Materials and methods

Study area

The Teacapan-Agua Brava-Las Haciendas mangrove-estuarine complex, also known as Marismas Nacionales, lies at the entrance of the Gulf of California, on the Pacific coast of Mexico, between the states of Sinaloa to the north and Nayarit to the south (Fig. 1). The mangrove habitat found within this system is believed to be the most extensive one on the Pacific coast of the Americas, covering approximately 80,000 hectares of mangroves and 200,000 hectares of seasonal floodplains (Blanco y Correa et al. 2011). There are three primary species of mangroves present in this system: the black mangrove (*Avicennia germinans*), which thrives in hypersaline soils (Flores-Verdugo et al. 2018); the red mangrove (*Rhizophora mangle*) (Kovacs et al. 2013), which prefers tidal creeks and strong hydrodynamic environments (Flores-de-Santiago et al. 2017), and the white mangrove (*Laguncularia racemosa*), which is found in areas with less tidal influence (Flores-de-Santiago et al. 2023). The climate along the coastline of this complex is tropical sub-humid, with a mean annual temperature of 25 °C (INEGI 2016). The overall rainfall in the area varies from 850 mm in the north to around 1660 mm near the San Pedro River mouth (CONAGUA 2019). The hurricane season, which runs from May to September, brings the maximum rainfall, leading to a seasonally marked flooding pulse (Vizcaya-Martínez et al. 2022).

Marismas Nacionales has been influenced by twelve rivers (Valderrama-Landeros et al. 2020). Among them, the Acaponeta and San Pedro rivers, situated in the central and southern parts of the area, are the only ones with no obstructions (hydro-electric dams) throughout their watershed (Valderrama-Landeros and Flores-de-Santiago 2019). The Marismas Nacionales complex is unique in its geomorphological feature of 280 parallel beach ridges between the Cautla Canal and the San Pedro River mouth, separating the mangrove forests within the coastal lagoon from the shoreline of the Pacific coast (Curray et al. 1969).

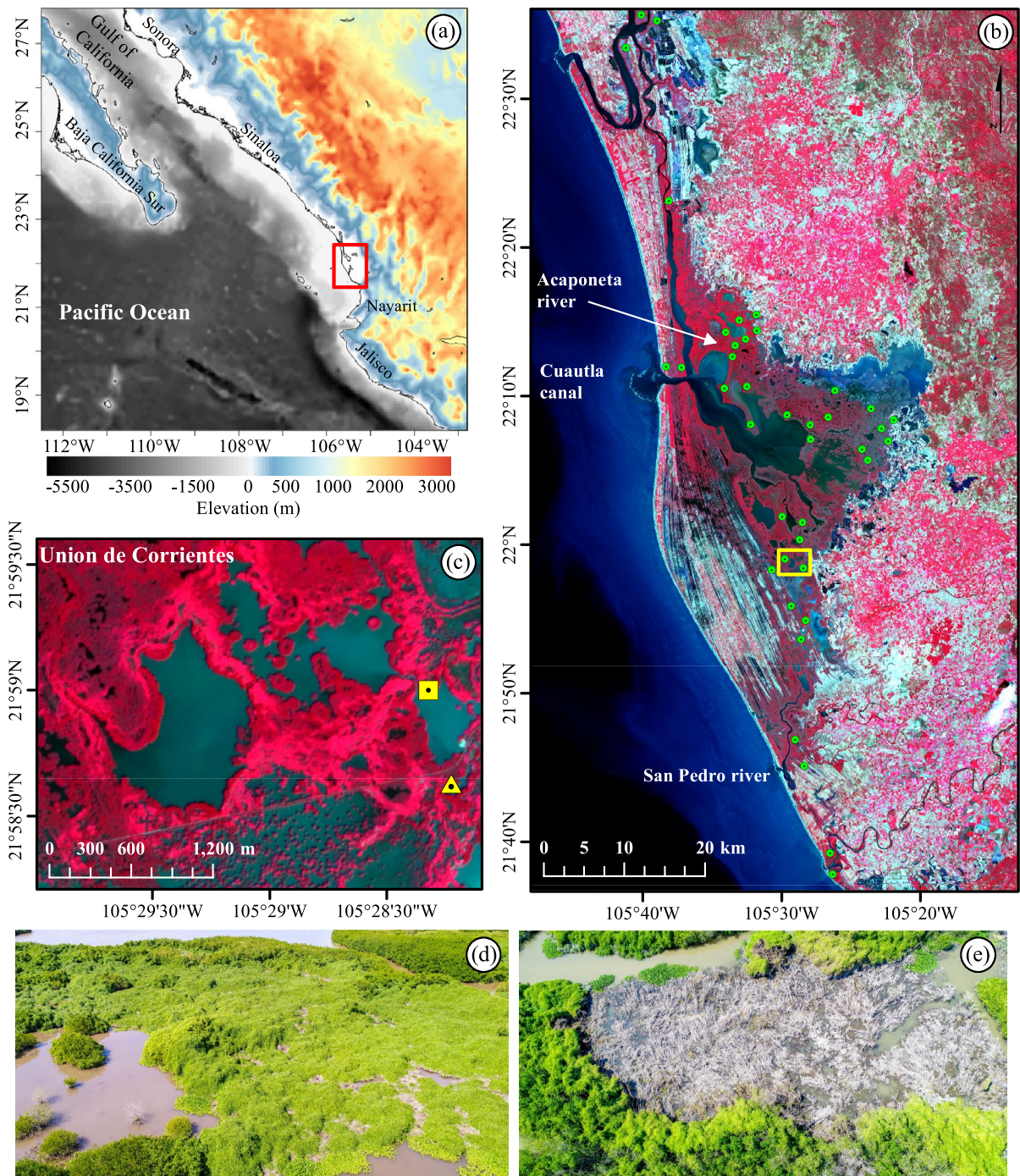
Field investigation and environmental data acquisition

On November 2, 2021, we undertook an initial reconnaissance field visit at the Union de Corrientes site (Fig. 2) to verify the presence of *Cissus verticillata* in the mangrove forest canopy. To conduct a comprehensive survey of the area, we utilized a DJI Phantom-4 Advanced UAV equipped with its embedded visible camera. The purpose of the manual flights was solely as a field reconnaissance approach by capturing aerial images from diverse perspectives. We used four high-capacity lithium batteries to supply power to the UAV, enabling a total flight duration of approximately 80 min. The UAV flights were manually controlled from a nearby concrete dock, covering an extensive area of approximately 100 hectares, in accordance with recommendations by Flores-de-Santiago et al. (2020) for semiarid wetland monitoring surveys.

To determine whether environmental factors influence the phenology of *Cissus verticillata*, we acquired data on the total rainfall (mm) and atmospheric temperature (°C) at a 2-m ground elevation for the southern section of Marismas Nacionales over a five-year period spanning from January 2019 to January 2024. These data were obtained at two-hour intervals utilizing the ERA 5-Land dataset provided by the Copernicus Climate Change Service initiative (<https://cds.climate.copernicus.eu/>). Following the data collection, we computed the monthly average values for both environmental variables with Origin Lab software.

Remote sensing data collection, analysis, and validation

The Sentinel-2 sensor has a 5-day revisit time and provides multispectral data with a spatial resolution of 10 m/pixel in 13 bands: coastal aerosol, blue, green, red, three in Red-Edge, two in near-infrared, water vapor, and three in short wave infrared (Cao et al. 2023). After the initial reconnaissance field visit, we calculated the Chlorophyll Index Red-Edge (CIRE) by extracting the near-infrared (NIR) and red-edge (RE) bands from the Sentinel-2 sensor through the Google Earth Engine data catalog (<https://earthengine.google.com/>). Google Earth Engine is a robust cloud-based platform for processing and analyzing spatial data. It provides access to extensive



spaceborne data such as Landsat, MODIS, and Sentinel-2, enabling users to visualize data, perform complex algorithms, and conduct large-scale environmental studies at unprecedented scales (Mutanga and Kumar 2019).

We selected the CIRE index based on its direct relation with the leaf chlorophyll content (Gitelson et al. 2003) and leaf area index (Qiao et al. 2020), considering that previous studies in the area had indicated the strong sensitivity of CIRE to phenological

Fig. 1 **a** Digital elevation model (m) of the northwestern coast of Mexico based on freely available TOPEX data (https://topex.ucsd.edu/cgi-bin/get_data.cgi). The red rectangle indicates the location of the Marismas Nacionales system. **b** Marismas Nacionales coastline based on a Sentinel-2 image dated February 4, 2024 (near-infrared, red, and green bands). The small yellow rectangle shows the location of the Union de Corrientes prefecture. The green circles indicate the 40 locations of the field sample validation sites **c** The Union de Corrientes mangrove system within the San Pedro River basin from an enhanced PlanetScope image dated November 2, 2021. The small yellow square and triangle indicate the approximate field-of-view of aerial images taken on **d** and **e**, respectively. The **d** image depicts a *Rhizophora mangle* forest recently covered by *Cissus verticillata*, while the **e** image shows a degraded mangrove area by the same plant species—taken on November 2, 2021

variations in mangrove canopy conditions (Valderrama-Landeros et al. 2021) and tropical vegetation (Liu et al. 2024). We selected several pixels at specific locations over *Cissus verticillata* areas in the Union de Corrientes region. The CIRE was calculated using the following equation, spanning from January 2019 to January 2024.

$$CIRE = \frac{NIR}{RE} - 1 \quad (1)$$

The final map was generated by consolidating the median pixel values from all available Sentinel-2 images in the Google Earth Engine cloud-computing platform during the optimal season for detecting *Cissus verticillata*, as determined by the CIRE index time series and Sentinel-2 bands. We then used these median pixel values, from the composite image, in a supervised classification by means of the Random Forest algorithm to categorize ten thematic classes across the entire area of Marismas Nacionales (Table 1). The Random Forest algorithm has been a widely used method for mangrove forest classification at the species level in this region, yielding favorable results when the appropriate time of the year is selected and accordant with the phenological trend of each species (Valderrama-Landeros et al. 2021). We based the selection of these ten thematic classes on data collected during field work and 14 specific polygons for each represented class.

We conducted 40 field surveys to validate the identification of *Cissus verticillata* throughout the Marismas Nacionales coastal system (Fig. 1b) on March 11–18, 2023; October 2–13, 2023; February 8–16, 2024; and May 26–31, 2024. At these

stations, we manually utilized a Matrice 300 RTK UAV equipped with a Parrot Sequoia camera to confirm the presence of *Cissus verticillata*. We also performed an identical analysis for the 2019 composite image, focusing on the period from October to December, matching the approach taken for the 2021 composite image.

Results

The atmospheric temperature and rainfall time series exhibited similar patterns, both showing maximum values of 30 °C and 150 mm from July to September (Fig. 3). Notably, the time series for the CIRE index of *Cissus verticillata* also reflected a comparable trend with these environmental variables, even though the cross-correlation analysis showed that there was a discrepancy between the environmental variables and the CIRE index—a three-month misalignment for atmospheric temperature ($r=0.68$) and two months for rainfall ($r=0.66$).

Based on the analysis of atmospheric temperature, rainfall, and CIRE index time series, we separated the Marismas Nacionales area into four distinct study periods: the dry-cold interval spanning from January to March, the dry-warm interval from April to June, the warm-wet interval from July to September, and the wet-cold interval from October to December (Fig. 4). The reflectance curves of the different thematic classes exhibited substantial variations across the four distinct periods, particularly in the RE and NIR bands within classes containing vegetation. Although the *Rhizophora mangle* class (Mangrove 1) displayed the most pronounced reflectance during the dry-cold season, differentiation among the classes was unclear during the dry-warm period. In the warm-wet season, however, the deciduous class demonstrated the highest reflectance. Conversely, the *Cissus* class stood out with marked separation into two RE bands and two NIR bands during the wet-cold season when compared with the other vegetation classes.

Regarding the classification of Marismas Nacionales under optimal conditions for the identification of *Cissus verticillata* during the wet-cold season, we observed that this invasive plant covered a total area of 838.08 ha in 2021 (Table 2) and was predominantly located in the southern part of the study

Fig. 2 Flowchart for the *Cissus verticillata* detection in Marismas Nacionales, Mexico

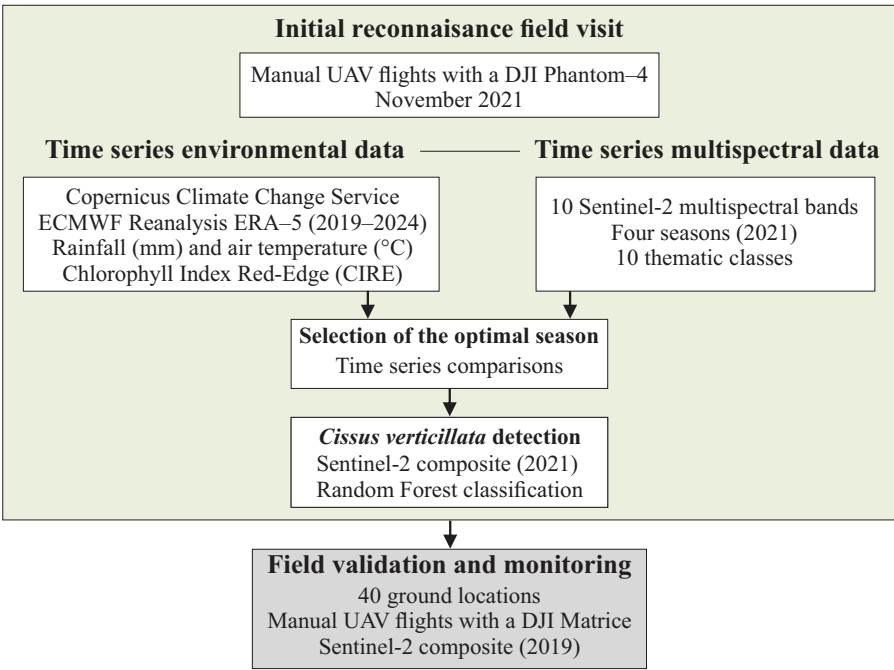


Table 1 Description of the thematic classes used for the Random Forest classification

Class	Description
Cissus	Sites predominantly dominated by <i>Cissus verticillata</i>
Mangrove 1	Mangrove forest sites with dominant <i>Rhizophora mangle</i>
Mangrove 2	Mangrove forest sites with other dominant species
Water	Areas with the presence of water
Wetland 1	Wetlands with herbaceous or shrubby halophytic vegetation
Wetland 2	Wetlands with sparse cover of shrub vegetation and high humidity
Bare soil	Sites without vegetation or urban areas
Deciduous	Areas with the presence of low deciduous forest canopy
Cropland 1	High-density non-woody crops (e.g., wheat, tobacco)
Cropland 2	Orchards and plantations with woody vegetation (e.g., mangoes)

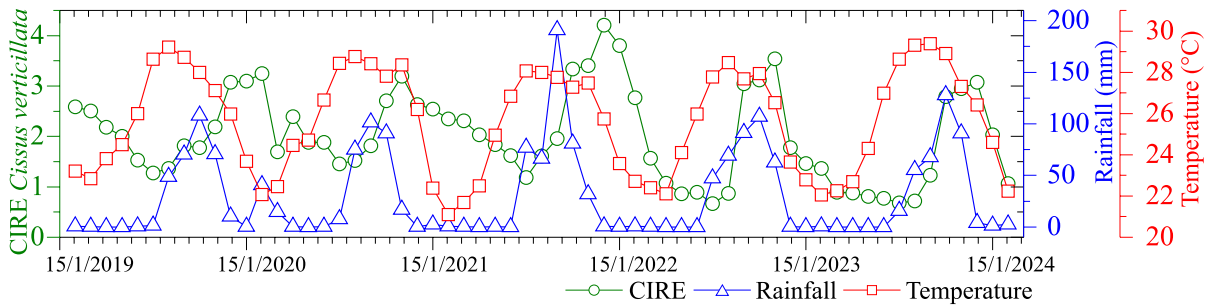


Fig. 3 Time series of the Chlorophyll Index-Red Edge (CIRE) for *Cissus verticillata*, rainfall, and atmospheric temperature from January 2019 to January 2024

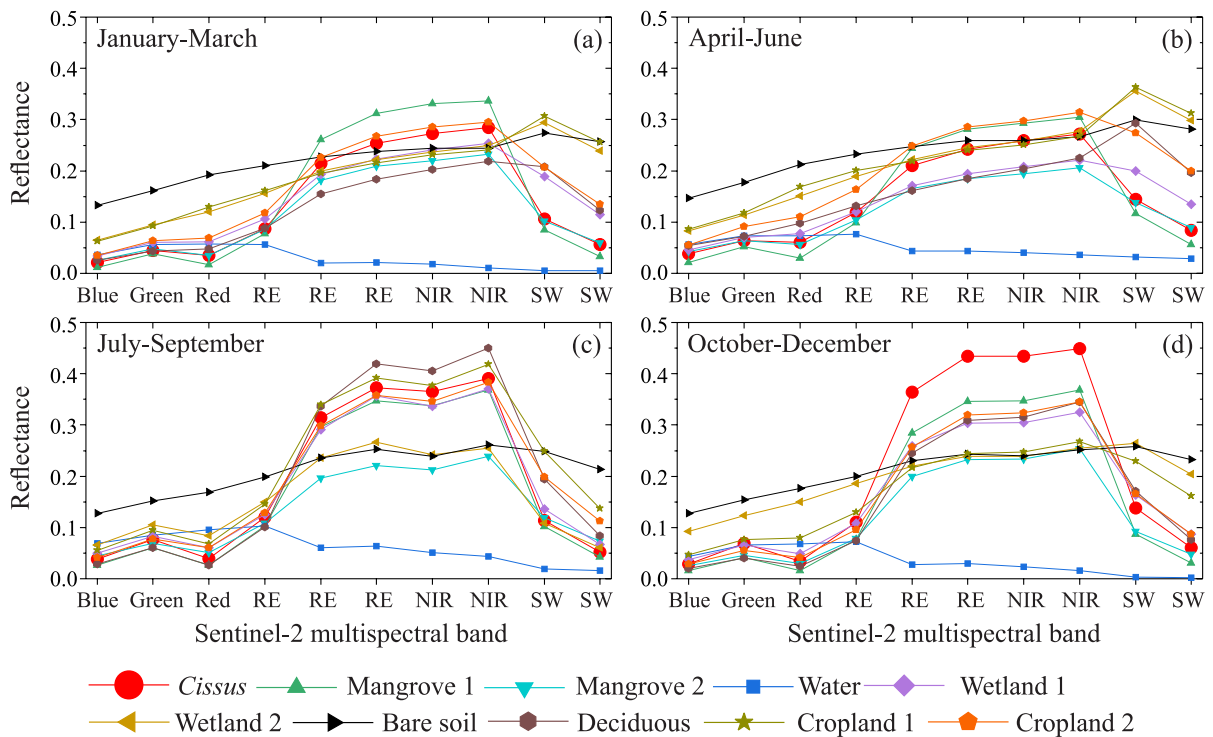


Fig. 4 Reflectance of the ten thematic classes analyzed based on the Sentinel-2 sensor bands at four different times of the 2021 year (**a** January to March, **b** April to June, **c** July to Sep-

tember, and **d** October to December). RE (Red-Edge), NIR (near infrared), and SW (shortwave infrared)

Table 2 Land cover class area for the Random Forest classification in 2021

Class	Area (ha)
Cissus	838.08
Mangrove 1	19,732.43
Mangrove 2	46,596.16
Water	116,435.35
Wetland 1	14,853.82
Wetland 2	27,161.63
Bare soil	74,077.8
Deciduous	57,691.95
Cropland 1	40,317.71
Cropland 2	47,873.02

area, as well as near the mouth of the Cuautla Canal (Fig. 5). These areas encompass the Acaponeta riverbank in the north and the San Pedro riverbank in the south. While we expected to detect *Cissus verticillata* in the Unión de Corrientes region (Fig. 5b), which was the pilot test area, the classification results led

to the discovery of this invasive plant in the Acaponeta River (Fig. 5c). For instance, even though *Cissus verticillata* is commonly observed in the fringe trees of *Rhizophora mangle* along the San Pedro River, it had also extended into the canopy of other mangrove species, such as *Laguncularia racemosa* in the Acaponeta River. The distribution of *Cissus verticillata* tends to be non-uniform, typically covering scattered areas in isolated and hard-to-reach locations, such as islands and inland floodplains. Nevertheless, the presence of *Cissus verticillata* in more inland mangrove species, such as *Avicennia germinans*, was minimal (Fig. 5d).

Within the 40 selected training sites for the monitoring of mangrove forests, we detected the presence of *Cissus verticillata* in all the locations along the banks of the Acaponeta and San Pedro rivers. On the other hand, we confirmed its absence in the remaining stations throughout Marismas Nacionales, which matched the overall classification map. The findings of the other thematic classes were consistent with previous reports on Marismas Nacionales, such as

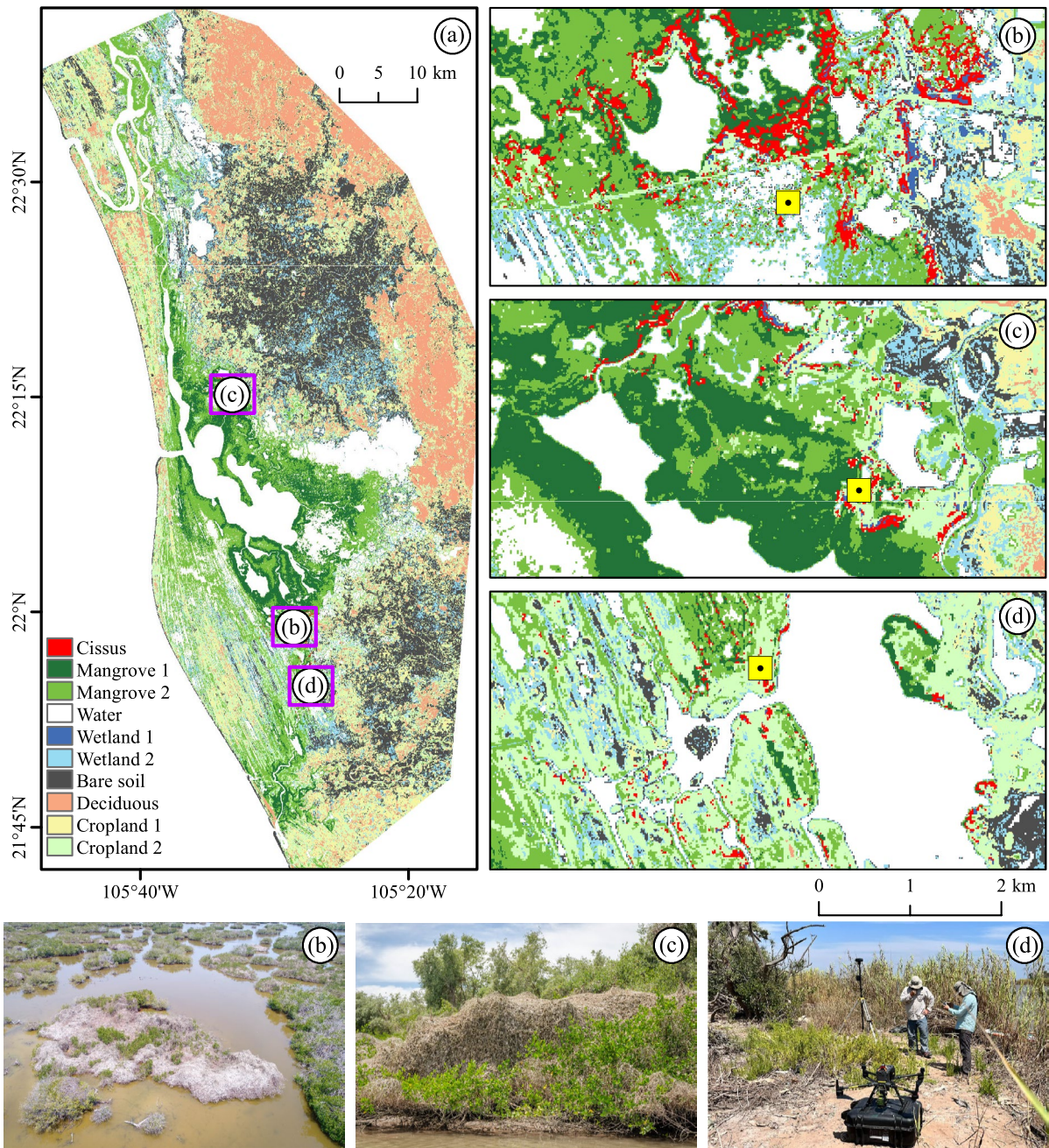


Fig. 5 **a** Random Forest classification using Sentinel-2 data from a composite image between October and December 2021. The magenta squares **b–d** indicate examples of representative locations where *Cissus verticillata* was detected. The yellow square depicts the location of the field photos representing **b**

Rhizophora mangle islands at the southern section of Unión de Corrientes site (May 28, 2024), **c** *Laguncularia racemosa* trees along the Acajoneta riverbank (April 13, 2023), and **d** sparse locations within the San Pedro watershed near the island of Mexcaltitán (April 19, 2023)

an extensive floodplain along the rivers, a myriad of agricultural fields near the towns, and a substantial extension of deciduous forests in uninhabited areas.

Between the years 2019 and 2021, there was a notable expansion in the distribution of *Cissus verticillata* (Fig. 6). The area occupied by this species

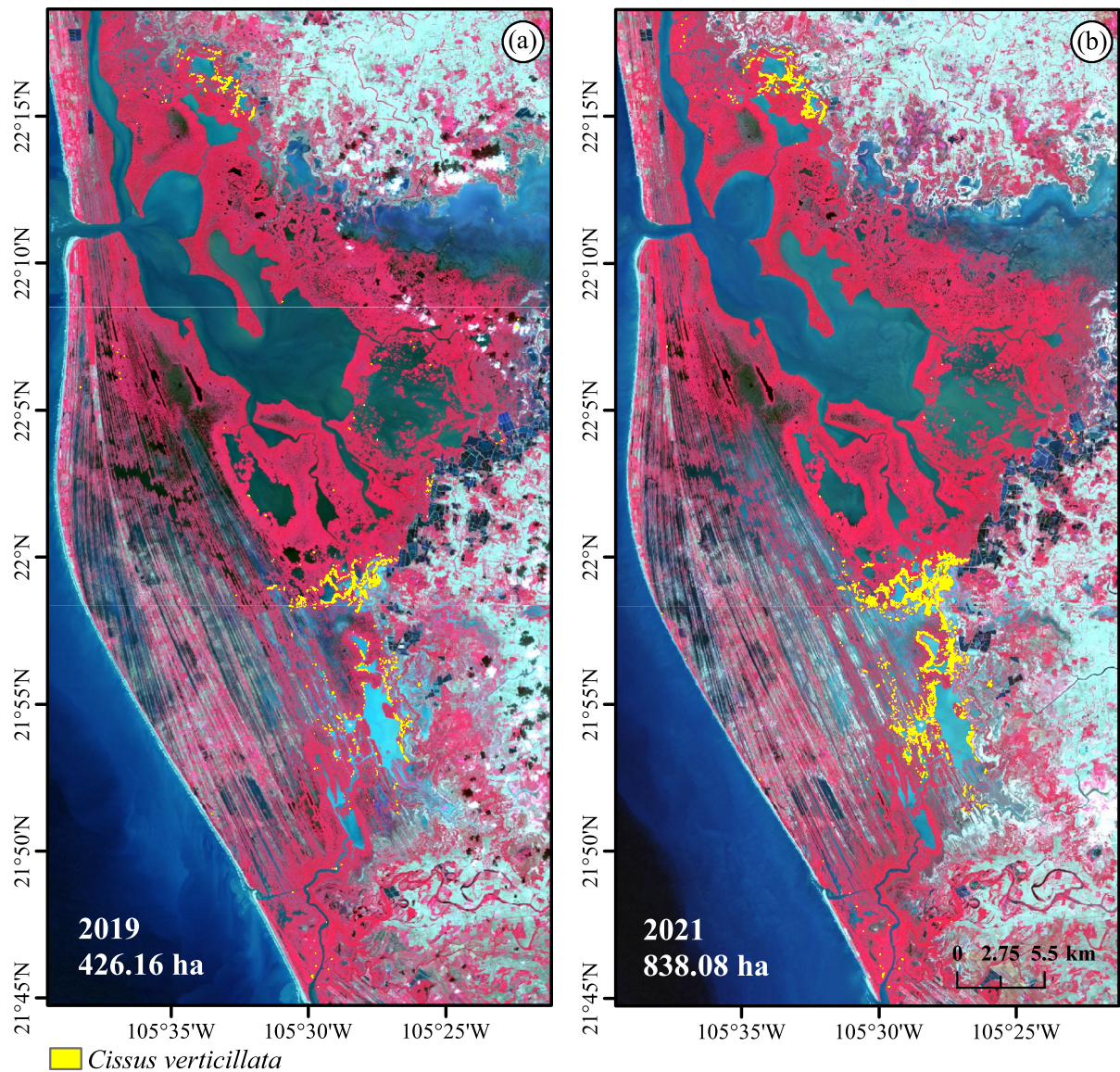


Fig. 6 *Cissus verticillata* locations identified in 2019 (a) and 2021 (b). The background satellite images are for visual reference only enhanced (near-infrared, red, and green bands).

increased from 426.16 ha in 2019 to 838.08 ha by 2021. This growth indicates that the species nearly doubled its habitat, suggesting successful adaptation and potentially favorable environmental conditions that contributed to its spread during this period. This growth has predominantly occurred within the same geographic locations, particularly at the confluences of the Acaponeta River to the north and the San Pedro River to the south.

Images were acquired from the Sentinel-2 sensor on November 22, 2019 (a) and November 21, 2021 (b)

Discussion

As expected, traditional field-based surveys for large study areas in wetland environments can be costly, non-feasible, and time-consuming (Cavalli 2024). Therefore, the map produced from multispectral data provides a more comprehensive interpretation of the spatial arrangement of *Cissus verticillata* in locations that had been previously unidentified. Although

our study encountered certain limitations due to the 10 m per pixel spatial resolution, the quality of this resolution has been a remarkable improvement over the Landsat program with its 30-m pixels (Ayushi et al. 2024), let alone the commonly used MODIS sensor with its broad 250-m pixel size (Valderrama-Landeros et al. 2024a). Nevertheless, the minimum sampling area of 100 m² could prove to be a challenge for detecting small patches of *Cissus verticillata* accurately. A potential solution could involve using higher spatial resolution sensors, such as the WorldView-2 (1.8 m per pixel), which, however, is extremely expensive (Valderrama-Landeros et al. 2018). Another more feasible option could be the use of daily PlanetScope data, which offer a higher 5-m spatial resolution (Nguyen et al. 2022), even if it must be highlighted that, unlike the Sentinel-2 data, access to these images entails a cost. In this case, institutional agreements or educational licenses can be a possible option in small target areas to enable the use of such images based on specific criteria (Valderrama-Landeros et al. 2022). Finally, Unmanned Aerial Vehicles (UAV) are advanced instruments extensively employed to detect invasive plant species in wetlands (Jochems et al. 2021) and riparian environments (Michez et al. 2016), having as primary drawback the challenge of conducting recurring studies in large areas (Flores-de-Santiago et al. 2020).

The time series analysis of environmental variables and the CIRE index of *Cissus verticillata* yielded the expected outcomes. Since it is known that *Cissus verticillata* thrives in environments with abundant freshwater (Drobnik and De Oliveira 2015), we expected the reflectance of photosynthetic pigments to be highest after the rainy season. This phenological pattern was of utmost importance to identify the invasive plant, as its peak reflectance from October to December does not align with the maximum photosynthetic pigment contents in mangrove species in this location (Valderrama-Landeros et al. 2024b). Although there have been reports indicating that all of the mangrove species in the northern region of Marismas Nacionales exhibit their peak period from January to February (Valderrama-Landeros et al. 2021) we found that this period extends from January to March in the southern part.

The results of our study demonstrate that the combination of two RE and two NIR bands offer notable advantages for the detection and mapping

of *Cissus verticillata*. This approach also allows detecting unique spectral signatures associated with the invasive plant, enabling the more effective long-term monitoring and management of this species (Müllerová et al. 2017). *Cissus verticillata* is currently mainly confined to areas in close proximity to the Acaponeta and San Pedro rivers in Marismas Nacionales and has exhibited a remarkable capacity for thriving in forested areas, as well as along oligotrophic watercourses. As such, its spread into the mangrove forest canopy can be attributed to several contributing factors, including its inherent capacity to sprout new stems and roots with little effort when trimmed (Drobnik and De Oliveira 2015), the influence of some bird species as its primary vector for seed dispersal (Richardson and Rejmánek 2011), and, as seen in field work, the ability of its roots not only to confine their expansion to the mangrove canopy during the dry season—characterized by an elevation of water salinity—but to also proliferate following an increase in freshwater discharge from the river during the rainy season (French et al. 2003).

The absence of *Cissus verticillata* in the canopy of other mangrove species, such as *Avicennia germinans*, is probably due to its struggle to grow in hypersaline habitats with limited access to freshwater, added to the fact that the salt crystals that *Avicennia germinans* releases through its leaves (Flores-de-Santiago and Flores-Verdugo 2024) could directly affect the roots of the plant. When invading other mangrove areas, however, this invasive plant has been observed to impede sunlight and induce dehydration in the leaves of the mangrove, ultimately leading to a reduction in the canopy and potentially the death of the tree (Flores-De-Santiago et al. 2012). This makes the constant monitoring and analysis of its expansion essential for its efficient long-term management and/or eradication.

Conclusions

This study aimed to identify and locate an aggressive and invasive plant species, *Cissus verticillata*, in the largest mangrove system on the eastern Pacific coast. The multispectral data time series analysis from the Sentinel-2 sensor determined that the period following the rainy season is optimal for detecting the *Cissus verticillata* signal in the RE and

NIR bands. The invasive plant was most prominent in regions where *Rhizophora mangle* dwells along the banks of the San Pedro River and within the *Laguncularia racemosa* canopy along the Acaponeta River. This study successfully identified the *Cissus verticillata* signal and mapped its spread within the Marismas Nacionales estuarine system, offering valuable insights for decision-makers involved in long-term monitoring and eradication efforts of this plant. Given the presence of numerous problematic invasive plants and the widespread availability of spaceborne imagery, abundant opportunities arise for the remote detection of invasive plant species in other tropical regions. If other invasive plant species exhibit distinctive spectral or phenological characteristics, collaborations between invasion ecologists and remote sensing experts could yield valuable and useful findings.

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Author contributions All authors contributed to the study's conception and design. Luis Valderrama-Landeros, Samuel Velázquez-Salazar, Edgar Villeda-Chávez, and Francisco Flores-de-Santiago collected and analyzed data. Francisco Flores-de-Santiago, Morelia Camacho-Cervantes, and Francisco Flores Verdugo wrote the first draft of the manuscript, and all authors commented on previous versions. All authors read and approved the final manuscript.

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Data availability Data will be made available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

Ethical approval All ethical practices have been followed in relation to the development, writing, and publication of the article entitled "Detection of an invasive plant (*Cissus verticillata*) in the largest mangrove system on the eastern Pacific coast—a remote sensing approach" by Luis Valderrama-Landeros, Morelia Camacho-Cervantes, Samuel Velázquez-Salazar, Edgar Villeda-Chávez, Francisco Flores-Verdugo, and Francisco Flores-de-Santiago.

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