Botanical Sciences 102 (1): 1-25. 2024
DOI: 10.17129/botsci.3358

Received: June 12, 2023, Accepted: August 30, 2023
On line first: November 6, 2023

Review / Revisión

Approaches, potential, and challenges in the use of remote sensing to study mangrove and other tropical wetland forests

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Abstract
Tropical wetland forests are fragile ecosystems facing critical risks due to global warming and other anthropogenic threats. Hence, gathering accurate and reliable information on them is urgent. Although remote sensing has demonstrated great potential in studying terrestrial ecosystems, remote sensing-based wetland forest research is still in an early stage of development. Mapping wetland forests, particularly mangrove forests, was an initial goal of this approach and is a task that still faces methodological challenges. Initially based on aerial photography only, wetland forest mapping through remote sensing underwent explosive diversification after the launching of artificial satellites in the 1970s. Later, precision in wetland forest mapping increased with the combination of hyperspectral, multispectral, and high and very high-resolution imagery. Accurate delimitation of wetland forest extent is also necessary to assess their temporal dynamics (losses, gains, and horizontal displacement). Despite the prevalence of mapping studies, current remote sensing-based research on wetland forests addresses new questions and novel aims, such as describing and predicting wetland forest attributes through mathematical modeling. Although this approach has made substantial progress in recent decades, modeling and predicting wetland forest attributes remain insufficiently explored fields of research. Combining active and passive sensors is a promising alternative to provide a more accurate picture of these communities' attributes. In particular, LiDAR and radar-based technologies may help overcome difficulties encountered in older studies. In the future, we will witness conceptual and methodological progress that will enable us to surmount the remaining challenges.
Keywords: active sensors, passive sensors, prediction of community attributes, vegetation mapping, vegetation monitoring, vegetation structure.

Resumen
Los humedales arbóreos tropicales están críticamente amenazados por el calentamiento global y otras amenazas antropogénicas; por ello, urge recopilar información confiable sobre estas comunidades vegetales. Aunque la percepción remota ha demostrado gran potencial en el estudio de ecosistemas terrestres, la investigación de los humedales arbóreos con este enfoque requiere mayor desarrollo. El mapeo de los humedales arbóreos (particularmente manglares), que fue el objetivo inicial de este enfoque, aún enfrenta desafíos metodológicos. Inicialmente basado solo en fotografías aéreas, el mapeo de humedales arbóreos se diversificó explosivamente con el lanzamiento de satélites artificiales y la interpretación de imágenes de percepción remota. La precisión de los mapas de estas comunidades aumentó con el uso combinado de imágenes multiespectrales, hiperespectrales, de alta y muy alta resolución. Para evaluar la dinámica temporal (pérdidas, ganancias, desplazamiento horizontal) de los humedales arbóreos necesitamos delimitar de manera precisa su extensión. Aunque todavía se están cartografiando numerosos humedales arbóreos, la investigación actual de estos ecosistemas por percepción remota aborda nuevas preguntas y objetivos (*e.g.*, predecir los atributos comunitarios por medio de modelos matemáticos). A pesar de sustanciales avances recientes, el modelado y la predicción de los atributos de los humedales arbóreos siguen siendo temas poco explorados. La combinación de sensores activos y pasivos es una alternativa promisoria para evaluar con precisión los atributos de estas comunidades, y las tecnologías de radar y LiDAR pueden ayudar a superar dificultades enfrentadas en el pasado. Los avances conceptuales y metodológicos en el futuro permitirán superar los desafíos que aún persisten.
Palabras clave: estructura de la vegetación, mapeo de la vegetación, monitoreo de la vegetación, predicción de atributos comunitarios, sensores activos, sensores pasivos

The quantitative study of ecosystems provides essential information for their thorough understanding and proper management and conservation (Seppelt *et al*. 2011, Viani *et al*. 2017, Valtonen *et al*. 2021). Nonetheless, current knowledge about practically every ecosystem on Earth is far from satisfactory. An attractive alternative to advance in this regard is offered by remote sensing, a highly relevant science that studies the biophysical features of the terrain through the analysis of data acquired by remote sensors (Chinea 2002, Turner *et al*. 2003, Aplin 2004, Navulur 2007, Schowengerdt 2007, Mabwoga & Thukral 2014, Valderrama-Landeros *et al*. 2018, Chuvieco 2020). Remote sensing has fostered the study of ecosystems mainly by focusing on their plant cover, which is their most conspicuous component (Rasolofoharinoro *et al*. 1998, Hansen *et al*. 2013, Mezaal *et al*. 2017, Abdel-Hamid *et al*. 2018, Einzmann *et al*. 2021). Numerous studies on various aspects of the planet's vegetation through remote sensing have demonstrated the great potential of this discipline to identify, map and monitor plant communities and their attributes without having direct contact with the terrain (Chinea 2002, Aplin 2004, Xie *et al*. 2008, Wang *et al*. 2010, Hansen *et al*. 2013, Mabwoga & Thukral 2014, Song *et al*. 2016, Putut Ash Shidiq *et al*. 2017, Islam & Ma 2018, Einzmann *et al*. 2021).

Wetlands are among the most important and, at the same time, most critically endangered ecosystems of the world (Valiela *et al*. 2001, Islam 2010, Islam *et al*. 2014, Mabwoga & Thukral 2014, Al-Naimi *et al*. 2016, Mao *et al*. 2021). Climate change seriously threatens their persistence, and multiple human activities strongly impact them (Kovacs *et al*. 2009, Lee *et al*. 2014, Islam *et al*. 2014, Thomas *et al*. 2017, Cho & Qi 2023). Given the physical characteristics of their habitats and the peculiarities of the vegetation typical of these ecosystems, access to them is difficult, mainly when they cover extensive areas (Kuenzer *et al*. 2011, Sharma 2018). This difficulty explains to some extent the relatively low pace at which crucial information on their structure, composition, and conservation status is gathered; this is worrisome given their high rates of transformation and fast disappearance (López-Portillo & Ezcurra 2002, Flores Mejía *et al*. 2010, Hogarth 2007, Landgrave & Moreno-Casasola 2012, Steinbach *et al.* 2023). An additional property of wetland ecosystems is the high variation of their vegetation; from a practical perspective, such variation can be reduced to the distinction between those communities dominated by herbs (herbaceous wetlands) and those in which dominance is shared by several woody species (wetland forests; Figure 1), among which mangrove forests have received the most attention from vegetation ecologists (Moreno-Casasola *et al*. 2009, Infante Mata *et al*. 2011).

In recent decades, remote sensing has been increasingly used in the study of mangroves and other tropical wetland forests (*e.g.*, Aschbacher *et al*. 1995, Proisy *et al*. 2000, Couteron *et al*. 2005, Fatoyinbo & Armstrong 2010, Solórzano *et al*. 2018). Most studies have been based on the analysis of vegetation reflectance to delineate their spatial distribution and temporal dynamics (Huete 1988, Gao 1996, Foody *et al*. 2001, Foody 2003, Lu *et al*. 2004, Kuenzer *et al*. 2011, Valderrama-Landeros *et al*. 2018), while other aspects, for example, their internal structure, have received less attention. In this paper, we provide an overview of the different goals pursued and achievements in studying tropical wetland forests through remote sensing. The review compares conceptual and methodological approaches, whose variety has resulted in a broad gamut of information that would probably not exist without the available theoretical framework and analytical tools. The initial sections provide a brief synopsis of tropical wetland forests to clearly define the object of this review and a historical overview of the development of remote sensing-based wetland forest studies.

Mangrove and other tropical wetland forests in a nutshell

Forested wetland ecosystems usually occur in intertidal zones of tropical and subtropical regions of the World (Saenger *et al*. 1983, Tomlinson 1986, Kathiresan & Bingham 2001, Lin & Dushoff 2004, Hogarth 2007, Sharma 2018; Figure 2A). The most common forest type characterizing these ecosystems is called mangrove or mangal (*sensu* Macnae 1969). Mangroves are typically dominated by a handful of tree species to which the term mangrove is also commonly applied. Mangrove forests are strongly influenced by tidal dynamics and occur in environments with variable salinity, from nearly fresh to hypersaline, with their optimal development in brackish water (Blasco *et al*. 2001, Agráz-Hernández *et al*. 2006). Due to their morphological and physiological attributes, mangrove trees can tolerate high temperatures, salinity, and anaerobiosis in frequently flooded substrates (Tomlinson 1986, Hogarth

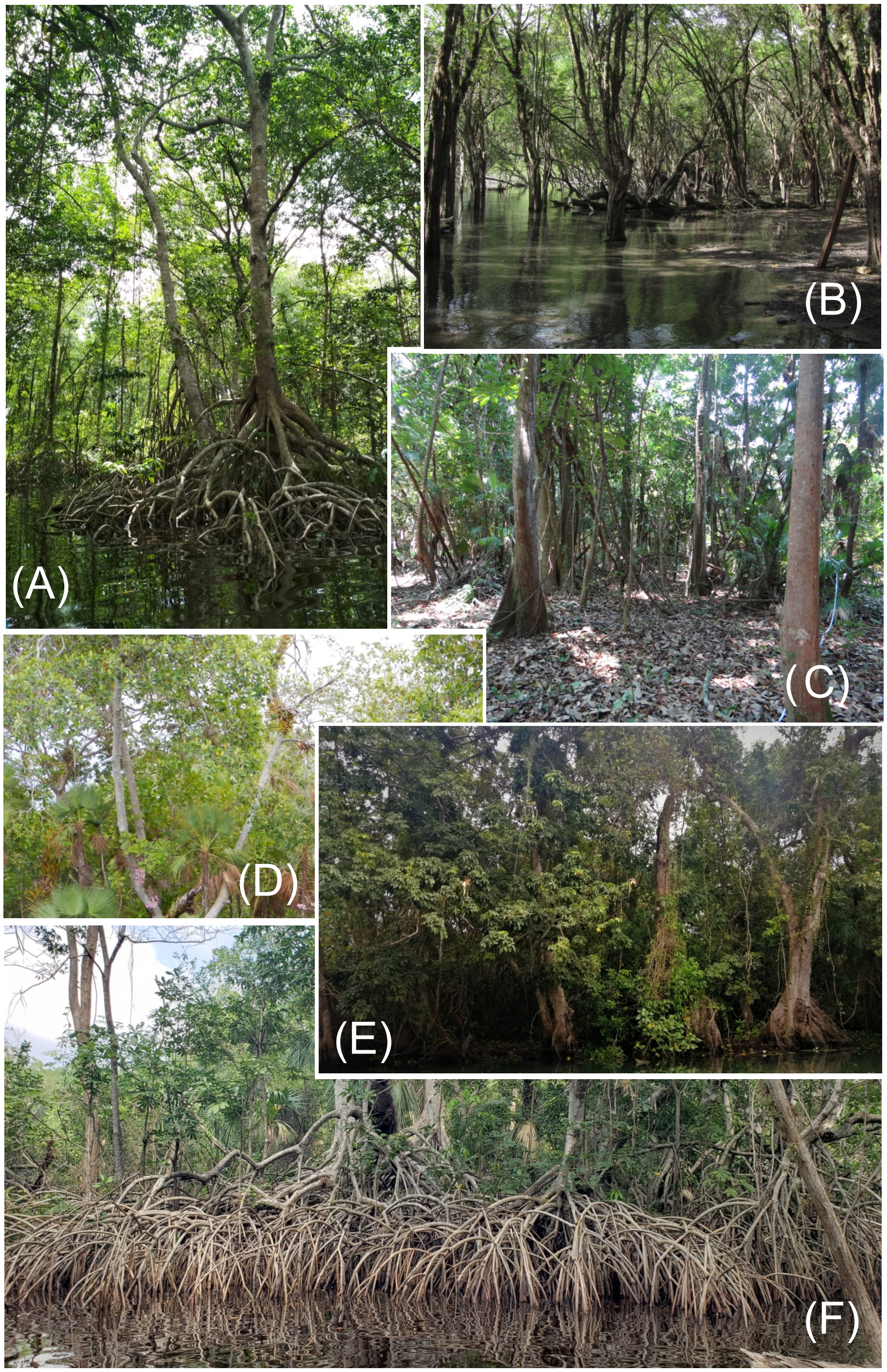

Figure 1. Images of tropical wetland forests in Mexico. Wetland forests encompass mainly mangroves but also other forests which are subjected to permanent or periodic flooding. (A) Mangrove forest dominated by *Rhizophora mangle* L. in Pantanos de Centla Biosphere Reserve, Tabasco. (B) Tintal (seasonally flooded forest dominated by *Haematoxylum campechianum* L.) in Nahá–Metzabok Biosphere Reserve, Chiapas. (C) Pukteal (seasonally flooded forest dominated by *Terminalia buceras* (L.) C. Wright), Pantanos de Centla Biosphere Reserve, Tabasco. (D) Wetland forest with tasiste palm (*Acoelorraphe wrightii* (Griseb. & H.Wendl.) H.Wendl. ex Becc.), Pantanos de Centla Biosphere Reserve, Tabasco. (E) Apompal (wetland forest dominated by *Pachira aquatica* Aubl.), Sontecomapan Lagoon, Veracruz. (F) Mangrove forest in El Cometa Lagoon, Tabasco. Photographs: Daniel Chávez (A), Jorge A. Meave (B, D), Derio Jiménez-López (C), Guillermo Ibarra-Manríquez (E), Jorge López-Portillo (F).

2007, Sharma 2018). These attributes include aerial roots that anchor plants in unstable substrates, respiratory roots (pneumatophores and lenticels) to increase access to atmospheric oxygen, regulation of water potential through variation of xylem salt concentration, stomatal regulation, and atmospheric water uptake, and salt secretion through specialized foliar glands (López-Portillo *et al*. 2014, Coopman *et al*. 2021), vivipary (germination on the branches of the parental tree), and hydrochorous dispersal of their propagules (Blasco *et al*. 2001, Kathiresan & Bingham 2001, Zhou *et al*. 2016). Although many of these physiological features also apply to non-mangrove wetland forests, these tend to develop in very low to no salinity conditions; their canopies are composed of a less limited number of tree and palm species, among which members of *Terminalia*, *Acoelorrhaphe* and *Pachira* are frequent (Figure 1C, D, E).

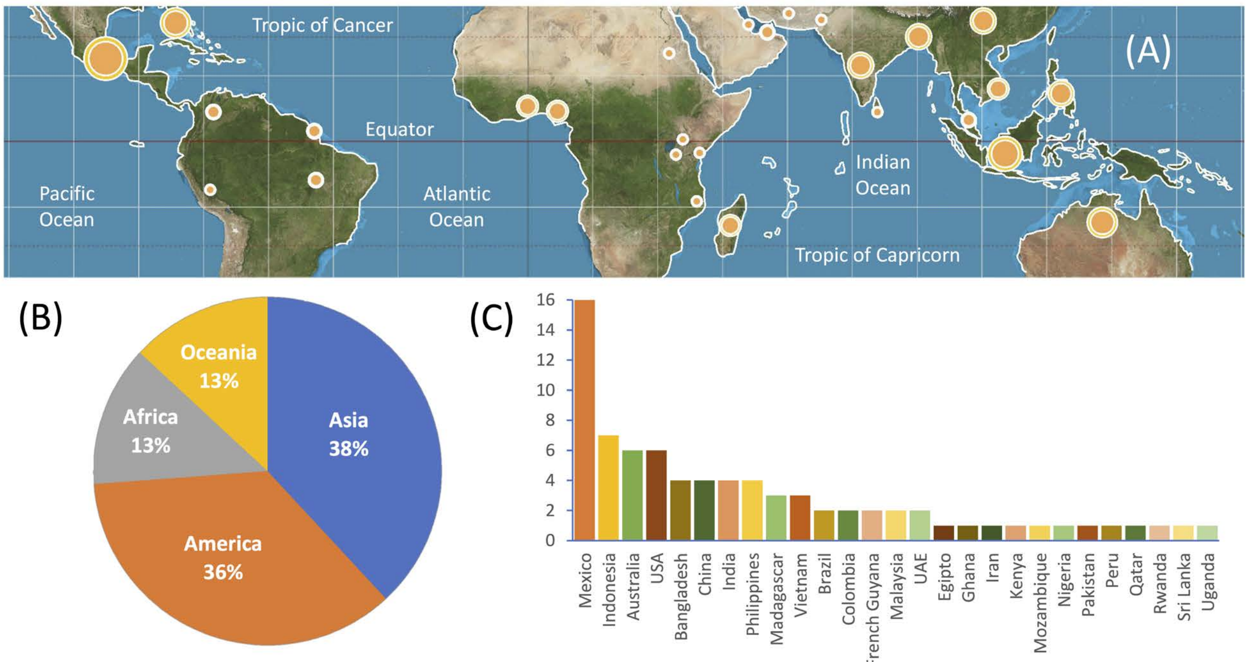

Figure 2. (A) Potential distribution of tropical wetland forests in the tropical regions of the world (30º N to 30º S). The white lines depict the coastlines of all continents where wetland forests may be found; due to scale, inland wetland forests are not shown (modified from Polidoro *et al*. 2010). Note the occurrence of wetland forests in arid regions of the world. The orange circles represent the locations (countries) of remote sensing-based wetland forest studies reviewed in this work; the circle size indicates the number of studies reviewed by country, according to the information shown in panel (C). (B) Continental distribution of the remote sensing-based wetland forest studies included in this review. (C) Distribution of these studies by country; USA, United States of America; UAE, United Arab Emirates. The fact of having recorded more studies from Mexico than from other countries is partly due to the higher ability of the authors to find more studies that were not easily accessible from this country. Map in (A) taken from Wikipedia (Strebe, CC BY-SA 3.0 <https://creativecommons.org/licenses/by-sa/3.0>, via Wikimedia Commons).

A notable feature of wetland forests compared with upland tropical forest types is their low species richness, particularly in the case of mangrove forests. Although species richness varies among biogeographical regions (Tomlinson 1986), the total known species richness for mangrove forests ranges from 55 to 73 taxa (Polidoro *et al*. 2010, Spalding *et al*. 2010), with Avicenniaceae and Rhizophoraceae being the most species-rich and abundant families (Hogarth 2007). Despite the relatively low tree diversity, wetland forests are recognized for their high productivity and the provision of essential ecosystem services (Whittaker & Likens 1973, Odum & Heald 1975, Tomlinson 1986, Kathiresan & Bingham 2001, Sharma 2018), including coastal protection, carbon sequestration, provision of habitat for migratory species, reproductive grounds for a specialized fauna including economically important species for fisheries, and provision of wood (Saenger *et al*. 1983, Lin & Dushoff 2004, Charcape-Ravelo & Moutarde 2005, FAO 2005a, Kuenzer *et al*. 2011).

Despite the unique character of wetland forests, their ecological fragility and high societal value, the present situation for most of them is alarming (Alongi 2008, Islam *et al*. 2014, Himes-Cornell *et al*. 2018). Factors responsible for their deterioration include both human activities (agriculture, cattle ranching, aquaculture, tourism) and natural phenomena, mainly tropical storms and climate change (Charcape-Ravelo & Moutarde 2005, Agráz-Hernández *et al*. 2006, Gilman *et al*. 2008, Kovacs *et al*. 2009, Cho & Qi 2023). These factors have significantly contributed to the loss of their cover worldwide (Polidoro *et al*. 2010), which in mangrove forests alone was between 20 and 35 % in the 1980-2005 period (Kathiresan & Bingham 2001, FAO 2005b, Hogarth 2007, Flores Mejía *et al*. 2010, Giri *et al*. 2011, Barbier *et al*. 2011), and have brought about a growing need to conserve and restore them. In this context, remote sensing is an option with great potential for efficiently studying mangroves and other wetland forests (Mahdavi *et al*. 2018).

Historical overview of remote sensing-based wetland forests studies

Early development of remote sensing took place in a military context (van der Meer *et al*. 2001). Nonetheless, remote sensing found its way since early times in ecosystem studies (Kumar *et al*. 2001). At first, aerial photographs were essential to assess and identify natural resources through forest inventories (West 1956, Colwell 1964, Aschbacher *et al*. 1995, Wang *et al*. 2019). Some inventories included mangrove cover of a region or country in thematic maps (*e.g.*, FAO 1963, Flores Mata *et al*. 1971, Vázquez-Yanes 1971, Blasco *et al*. 1998, Sulong *et al*. 2002, FAO 2005b, Valderrama *et al*. 2014). MacDonald *et al*. (1971) published one of the earliest examples of the use of radar imagery to study coastal landscapes.

With the launching of the first artificial satellites to explore the territory in the 1970s, remote sensing studies underwent explosive diversification, and their coverage expanded to the entire planet (Wulder *et al*. 2019). Interestingly, the first formal publications in remote sensing were seemingly related to the study of wetlands, some of which included mangrove forests (Eitel 1974, Butera 1983, Hardisky *et al*. 1986, Guo *et al.* 2017). To our knowledge, Biña *et al*. (1978) and Lorenzo *et al*. (1979) published the first analyses of spatial changes in mangroves and the monitoring of their deterioration in Southeast Asia based on Landsat images. The use of satellite imagery grew considerably during the following decade; the diversification of platforms (Landsat, SPOT, ERS-1, RADAR) increased the options to study and demarcate wetland forests, particularly mangrove communities (Herz & Jaskow 1985, Dutrieux *et al*. 1990, FAO 2005b, Lucas *et al*. 2007, Kovacs *et al*. 2008, Abdel-Hamid *et al*. 2018, Mahdavi *et al*. 2018). Over time, the remote sensing approach was applied to the study of mangroves in many tropical regions of the world (*e.g.,* Pasqualini *et al*. 1999, Saito *et al*. 2003, Kovacs *et al*. 2005, Satyanarayana *et al*. 2011: Figure 2B, C), with theoretical and technological tools providing higher-quality information on the status of vegetation at each locality (Zhang *et al*. 2023). More recently, community structural attributes of wetland forests (*e.g.*, aboveground biomass, canopy height) have been explored using mathematical modeling (Couteron *et al*. 2005, Kayitakire *et al*. 2006, Proisy *et al*. 2007), and LiDAR (Light Detection and Ranging; Owers *et al*. 2018, Pereira *et al*. 2018, Koma *et al*. 2021), although wetland forest mapping and monitoring continue to prevail (*e.g.*, Sulong *et al*. 2002, Saito *et al*. 2003, Adam *et al*. 2010, Barbier *et al*. 2011, Alsaaideh *et al*. 2013, Jones *et al*. 2016, Chatziantoniou *et al*. 2017, Guo *et al*. 2017, Yevugah *et al*. 2017, Roy *et al*. 2019, Li *et al*. 2023, Steenvoorden *et al.* 2023; Figure 3A).

Spatial delimitation and mapping of mangroves and other wetland forests

A fundamental aim in the study of mangroves and other wetland forests through remote sensing has been the definition of their spatial limits (Dale *et al*. 1996, Hirano *et al*. 2003, Yang *et al*. 2009, Margono *et al*. 2014, Wang *et al*. 2019, Steinbach *et al.* 2023), which is the basis for their cartographic expression (Figure 3A). This is a necessary step to understand the persistence of wetland forests or the changes in their spatial coverage over time (Kovacs *et al*. 2001, Guerra Martínez & Ochoa Gaona 2006, Ren *et al*. 2011, Mansaray *et al*. 2016, Maryantika & Lin 2017, Roy *et al*. 2019, Pan *et al*. 2020, Zhang *et al*. 2023). Aerial photography, Landsat, and SPOT imagery are among the most widely used inputs in the study of wetland forests due to their availability and continuity (Figure 3B; Tables 1, 2).

Most studies using satellite images are based on the analysis of vegetation reflectance (Fei *et al*. 2011, Kuenzer *et al*. 2011, Abdel-Hamid *et al*. 2018, Apostolopoulos *et al*. 2023) under the tenet of an existing relationship between reflectance values recorded in the image and terrain features (Colwell 1974). However, the rapid development and growth of other remote sensing technologies, in particular LiDAR, have unlocked new ways to explore how the various elements of ecosystem structure impact functional diversity and ecosystem services (Mascaro *et al*. 2011, Asner *et al*. 2012, Davies & Asner 2014, Owers *et al*. 2018). LiDAR is rapidly transitioning from a demonstrative concept to a pivotal tool for estimating carbon stocks in tropical forests (Asner *et al*. 2012) and is thus effective at generating accurate above-ground biomass maps for mangroves, enabling carbon stock assessment and facilitating coastal management (Pereira *et al*. 2018).

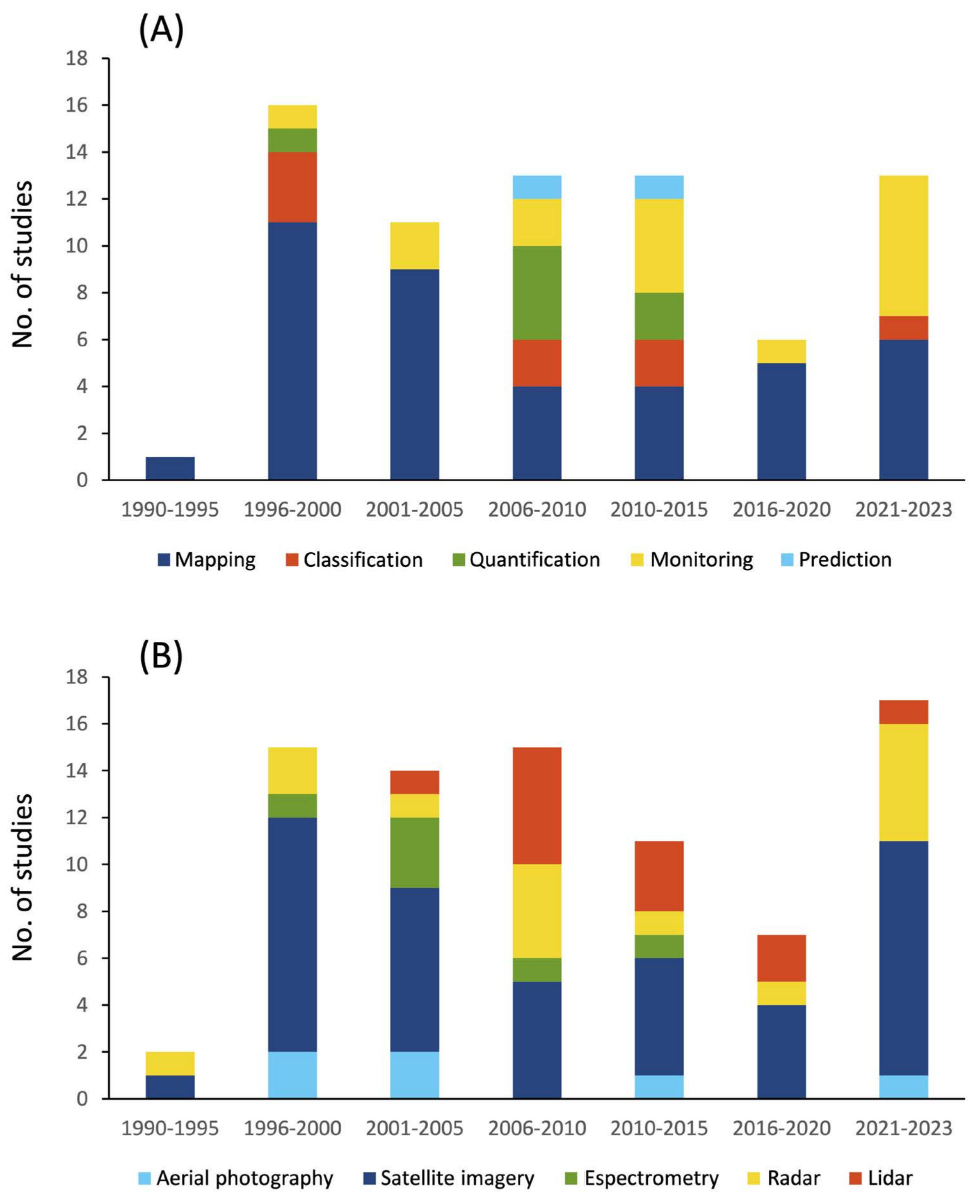

Figure 3. Temporal trends observed in remote sensing-based studies of wetland forests in the 1971-2023 period. (A) Temporal trends in the development of studies according to the main five goals identified in this review. (B) Temporal trend in the remote sensing inputs used by these studies.

Table 1. Classification of remote sensing-based wetland forests studies according to their main goals, resources, and platforms. Explanation of goals: Mapping, spatial delimitation of wetland forests on cartography; Classification, recognition of the different wetland types, including wetland forests, differing in structure, species composition, or health condition; Quantification, assessment of quantitative characteristics of wetland forests, particularly structural attributes; Monitoring, multi-temporal assessment of wetland forests properties to detect trends of change; Prediction, construction of models relating characteristics of the remote sensing resources and vegetation properties to predict forest attributes in sites lacking field data. See Table 2 for explanations of remote sensing input acronyms.

Remote sensing inputs	Mapping	Classification	Quantification	Monitoring	Prediction
Passive sensors					
Aerial photography	8, 20, 63, 85	7		12, 25, 51, 55, 85	
Satellite imagery					
Landsat	10, 15, 18, 19, 23, 48, 54, 58, 61, 70, 77.	11, 47, 73, 86	2, 35, 83	3, 13, 27, 29, 31, 43, 44, 53, 55, 60, 64, 68, 80, 81, 87, 91, 92, 93, 94	82
Sentinel-2	67, 70, 79, 84, 88, 89, 90		72	92	82
SPOT	5, 8, 9, 10, 14, 24, 70	47		4, 6, 12	
IKONOS	26, 28				34, 46
QuickBird	26, 41	38		80	
Google Earth	58, 66				
RapidEye			72		
Hyperion		57		76	
Planetscope			72		
WorldView	65, 70			51	
Kompsat			75		
ICESAT	37				
Radiometer	24				
Spectrometer					
CASI	10, 21, 45				
AVIRIS	22				
ASD FieldSpec		52			
Field Spec Pro		39			

Remote sensing inputs	Mapping	Classification	Quantification	Monitoring	Prediction
Active sensors					
Radar					
Sentinel-1	84, 88, 90	86			
Polarimetric Radar	1, 5, 16, 17, 71	11, 47		69	
AIRSAR	21				
ENVISAT ASAR	36				
SRTM	30, 37		35	91	
ERS-1 SAR	16			69	
PALSAR	54, 58	50	33	69	
LIDAR	42, 56, 59, 63, 78		49	62, 87	
GLAS	37, 78				

[1]MacDonald *et al.* (1971), [2]Bina *et al.* (1978), [3]Lorenzo *et al.* (1979), [4]Dutrieux *et al.* (1990), [5]Aschbacher *et al.* (1995), [6]Ramsey III & Jensen (1996), [7] Dale *et al.* (1996); [8]Blasco *et al.* (1998), [9]Gao (1998), [10]Green *et al.* (1998b), [11]Ramsey III *et al.* (1998), [12]Rasolofoharinoro *et al.* (1998), [14]Pasqualini *et al.* (1999), [15]Koutsias *et al.* (2000), [16]Kushwaha *et al.* (2000), [17]Proisy *et al.* (2000), [18]Kovacs *et al.* (2001), [19]Foody *et al.* (2001), [20]Sulong *et al.* (2002), [21]Held *et al.* (2003), [22]Hirano *et al.* (2003), [23]Hossain *et al.* (2003), [24]Saito *et al.* (2003), [25]Dahdouh-Guebas *et al.* (2004), [26]Wang *et al.* (2004); [27]Hernández Cornejo *et al.* (2005), [28]Kovacs *et al.* (2005); [29]Berlanga-Robles & Ruiz-Luna (2006), [30]Simard *et al.* (2006), [31]Berlanga-Robles & Ruiz-Luna (2007), [32]Jensen *et al.* (2007), [33]Lucas *et al.* (2007), [34]Proisy *et al.* (2007), [35]Fatoyinbo *et al.* (2008), [36]Kovacs *et al.* (2008), [37]Simard *et al.* (2008), [38]Myint *et al.* (2011), [39]Wang & Sousa (2009), [40]Yang *et al.* (2009), [41]Kovacs *et al.* (2009), [42]Fatoyinbo & Armstrong (2010), [43]Berlanga-Robles & Ruiz-Luna (2011), [44]Giri *et al.* (2011), [45]Kamal & Phinn (2011), [46]Satyanarayana *et al.* (2011), [47]Fei *et al.* (2011), [48]Alsaaideh *et al.* (2013); [49]Wannasiri *et al.* (2013); [50]Darmawan *et al.* (2014); [51]Heenkenda *et al.* (2014); [52]Zhang *et al.* (2014); [53]Mabwoga Thukral (2014); [54]Margono *et al.* (2014); [55]Valderrama *et al.* (2014), [56]David & Ballardo (2015), [57]Demuro & Chisholm (2015), [58]Aslan *et al.* (2016), [59]David & Ballardo (2016), [60]Jia *et al.* (2016), [61]Jones *et al.* (2016), [62]Pada *et al.* (2016), [63]David & Ballardo (2016), [64]Mansaray *et al.* (2016), [65]Shahzad *et al.* (2017), [66]Yevugah *et al.* (2017), [67]Chatziantoniou *et al.* (2017), [68]Maryantika & Lin (2017), [69]Thomas *et al.* (2017), [70]Valderrama-Landeros *et al.* (2018), [71]Abdel-Hamid *et al.* (2018), [72]Baloloy *et al.* (2018), [73]Gupta *et al.* (2018), [74]Islam & Ma (2018), [75]Solórzano *et al.* (2018), [76]Pandey *et al.* (2019), [77]Roy *et al.* (2019), [78]Hu *et al.* (2020), [79]Mahdianpari *et al.* (2020), [80]Pan *et al.* (2020), [81]Mao *et al.* (2021), [82]Nguyen & Nguyen (2021), [83]Nguyen *et al.* (2021), [84]De Luca *et al.* (2022), [85]Apostolopoulos *et al.* 2023, [86]Cho & Qi (2023), [87]Flores-de-Santiago *et al.* (2023), [88]Hemati *et al.* (2023), [89]Li *et al.* (2023), [90]Pham *et al.* (2023), [91]Shafi *et al.* (2023), [92]Steinbach *et al.* (2023), [93]Waleed *et al.* (2023), [94]Zhang *et al.* (2023).

Efforts to map mangroves and other wetland forests have faced methodological challenges due to their highly variable spectral characteristics and similar reflectance spectra with the underlying soil (Adam *et al*. 2010, Shahzad *et al*. 2017). Early studies pursuing this goal based on Landsat imagery (Biña *et al*. 1978, Lorenzo *et al*. 1979) produced results fraught with significant uncertainty in setting the spatial limits of these communities. This situation improved with the development of new sensors with higher spatial and spectral resolution (Table 3), allowing greater precision to discriminate mangroves from other types of cover (Aschbacher *et al*. 1995, Gao 1998, Blasco *et al*. 1998, Pasqualini *et al*. 1999). At the turn of the century, the availability of very high-resolution imagery (*i.e.*, pixels < 4 m; QuickBird, GeoEye-1, Worldview-2) opened the possibility to map wetland forests areas in greater detail; however, aerial photography is still being used (Sulong *et al*. 2002, Hirano *et al*. 2003, Wang *et al*. 2004, Guo *et al*. 2017), mainly because of their potential to discriminate the different species that occur in these communities (Kamal & Phinn 2011, Valderrama-Landeros *et al*. 2018).

The platforms for acquiring satellite imagery are classified as passive sensors because they use solar radiation to capture terrain details. Other types of sensors are known as active because they emit energy and record its reflection, rendering them independent from physical and weather conditions at image acquisition, such as illumination, cloudiness, and water bodies (Aschbacher *et al*. 1995, Green *et al*. 1998a, Chinea 2002, Kovacs *et al*. 2008, Kuenzer *et al*. 2011, Li *et al*. 2023). Interestingly, recognizing the advantages of contrasting sensor types led to their combined use (Held *et al*. 2003, Asner *et al*. 2008, Simard *et al*. 2008, Aslan *et al*. 2016), increasing the capacity and efficacy to detect, differentiate and estimate wetland forest structure (Ramsey III *et al*. 1998, Rasolofoharinoro *et al*. 1998, Kayitakire *et al*. 2006, Aslan *et al*. 2016, Wang *et al*. 2019, De Luca *et al*. 2022, Steenvoorden *et al*. 2023). Likewise, precision in mangrove and other wetland forests mapping has improved by combining hyperspectral with multispectral, high, and very high-resolution images (Apostolopoulos *et al*. 2023). This procedure allows the detection of the spectral signature (Shaw & Burke 2003, Navulur 2007, Pandey *et al*. 2019) and a more accurate location of precise wetland forest limits (Blasco *et al*. 1998, Hossain *et al*. 2003, Adam *et al*. 2010).

Monitoring wetland forest dynamics

The possibility of accurately delimiting the territorial extent of wetland forests is also relevant when aiming to assess their losses or gains, as well as their horizontal displacements (Dahdouh-Guebas *et al*. 2004, Hernández Cornejo *et al*. 2005, Shafi *et al*. 2023). In remote sensing, one of the most popular methods for these goals is identifying the presence of a wetland forest through terrain reflectance values (Ingram *et al*. 1981, Ramsey III & Jensen 1996, Mahdavi *et al*. 2018, Wang *et al*. 2019). Although temporal differences in reflectance may represent variations in illumination, atmospheric conditions, and soil moisture, among other factors, there is no doubt that they also reflect changes in vegetation cover (Singh 1989).

Table 2. Explanation of acronyms of remote sensing inputs listed in Table 1 and Table 3.

Acronym	Explanation
SPOT	Satellite Pour l'Observation de la Terre
ICESAT	Ice, Cloud and Land Elevation Satellite
CASI	Compact Airborne Spectrographic Imager
AVIRIS	Airborne visible/infrared imaging spectrometer
AIRSAR	Airborne Synthetic Aperture Radar
ENVISTAT ASAR	ENVISAT Advanced Synthetic Aperture Radar
SRTM	Shuttle Radar Topography Mission
ERS-1 SAR	European Remote-Sensing Satellite-1 Synthetic Aperture Radar
PALSAR	Phased Array type L-band Synthetic Aperture Radar
LIDAR	Light Detection and Ranging
GLAS	Geoscience Laser Altimeter System

Interestingly, despite the large availability of satellite-based resources, aerial photography remains essential for monitoring wetland forest dynamics due to an extensive series of aerial photographs of coastal regions predating the satellite-dominated age of remote sensing. The combined use of aerial photographs with satellite images and Geographic Information Systems (GIS) has yielded accurate assessments of wetland areas reductions (Dahdouh-Guebas *et al*. 2004, Heenkenda *et al*. 2014, Apostolopoulos *et al*. 2023). However, when the period delimited for the analysis of wetland forest dynamics does not include the pre-satellite image era, the studies are based primarily on satellite imagery (Figure 3B). For example, in a multi-temporal analysis of landscape changes associated with coastal wetlands, Berlanga-Robles & Ruiz-Luna (2006, 2007, 2011) successfully assessed losses in wetland cover over a 20-yr period based on the use of the panchromatic bands of Landsat imagery. Using a similar approach, Giri *et al*. (2011) made a more precise assessment of the extent of wetlands worldwide, including both herbaceous and forested wetlands, which was used to update previous reports on these ecosystems by FAO (2005b) and correct previous overestimation. Through the amalgamation of LiDAR and other remote sensing techniques, Asner *et al*. (2008) not only identified and tracked invasive plant species but also evaluated their ecological impact and provided accurate geographical data for conservation and management initiatives. This latter approach holds a huge potential for identifying species in low-diversity ecosystems, such as wetland forests, where the possibility of confounding the radiometric signals from a multitude of species is much more limited than in species-rich upland tropical forests. New and more precise assessments of the extent and limits of wetland forests are needed to provide a more robust basis to evaluate coverage changes, particularly the losses, of these ecosystems worldwide (Shafi *et al*. 2023).

The increasingly accurate assessment of temporal changes in vegetation structure and other aspects of wetland forest communities has benefited from the use of vegetation indices, which consist of numerical relationships between different spectral bands in the images. Among the many existing indices, the most used in wetland forests studies are the Normalized Difference Vegetation Index (NDVI), the Enhanced Vegetation Index (EVI), and the Normalized Difference Water Index (NDWI) (McFeeters 1996, Gao 1998, Kovacs *et al*. 2005, Alsaaideh *et al*. 2013, Kafy *et al*. 2023, Shafi *et al*. 2023). By minimizing the effects of factors linked to biophysical terrain parameters, vegetation indices provide reliable multi-temporal information on the conservation status and the functionality of these systems (Gao 1996, Huete *et al*. 1997, Gao 1998, Saito *et al*. 2003, Wang *et al*. 2004, Nasiri *et al*. 2022, Li *et al*. 2023).

The launching of new technologies has enabled the use of more detailed sources of information (Pada *et al*. 2016, Tassi & Vizzari 2020, Pham *et al.* 2023). Along with the progress in image processing and classification techniques with new analytical algorithms, we have increased our capacity to assess temporal changes in wetland forests accurately (Heenkenda *et al*. 2014, De Luca *et al*. 2022, Pan *et al*. 2022, Shafi *et al*. 2023). Within this framework, one of the most promising developments for mapping and monitoring wetland forests is Google Earth Engine (GEE), a free cloud-based platform to process vast geospatial datasets that allows users to access, observe and analyze geospatial data across the entire planet (Gorelick *et al.* 2017, Tassi & Vizzari 2020, Kafy *et al*. 2023). The GEE platform contains petabytes of fully accessible images from multiple remote sensing platforms; it offers an enormous volume of Earth observation data and high-performance parallel computing equipment to analyze them (Rahaman & Shermin 2022, Hemati *et al*. 2023). Thus, one major advantage of operating on the GEE platform is a significant reduction in satellite image processing time, which in a short period has contributed to improving the assessment of land use and land cover change, on top of traditional mapping and vegetation monitoring efforts (Mahdianpari *et al*. 2020, Nasiri *et al*. 2022). In addition, the integration of machine learning algorithms into the GEE platform has considerably accelerated the gathering of valuable information about the state of wetland forests, and thus are handy new tools for the classification, mapping, and monitoring of these ecosystems compared to traditional methods (Tassi & Vizzari 2020, Waleed *et al*. 2023, Flores-de Santiago *et al*. 2023).

Modeling and predicting wetland forest community attributes through remote sensing

In the advancement of remote sensing, particularly concerning the study of vegetation, one of the most prominent developments refers to the use of the characteristics of digital images to model community diversity and structural attributes (*e.g.*, basal area, biomass, crown cover, stem density, species richness, canopy height) with various degrees of precision and certitude (Strahler *et al*. 1986, Woodcock & Strahler 1987, Chinea 2002, Chuvieco 2020). The basic tenet of vegetation attribute modeling from images acquired through remote sensors establishes the possibility of constructing algorithms relating image spectral features (*i.e.,* reflectance) with the physical attributes of the terrain (*e.g.,* Strahler *et al*. 1986, Woodcock & Strahler 1987, Nagendra & Rocchini 2008).

Table 3. Synthesis of the temporal, spatial and radiometric resolutions of the different remote sensing platforms used for the study of tropical wetland forests. Please note that for Landsat, Sentinel and Spot, the information for all the sensors used in their different missions is condensed and the resolutions are given as ranges. NA, not applicable.

Platform	Number of bands	Temporal resolution (days)	Spatial resolution (m)	Radiometric resolution (µm)*
Aerial photography	NA	Variable (on demand)	1	NA
Landsat	2 to 9	16 to 18	15 to 100	0.475 to 12.51
Sentinel-2	12	6 to 10	5 to 60	0.43 to 2.28
SPOT	4 to 5	26	1.5 to 20	0.45 to 1.75
IKONOS	4	14	1 to 4	0.45 to 0.90
QuickBird	5	2.8	0.65 to 2.4	0.45 to 0.90
RapidEye	5	1	5	0.4 to 0.85
Hyperion	220	1 to 2	10 to 30	0.4 to 2.5
PlanetScope	8	1	3	0.43 to 0.88
WorldView	9	1.1	0.5 to 2.0	0.45 to 0.9
Kompsat-2	4	28	1 to 4	0.45 to 0.9
ICESAT	NA	91	NA	0.532
CASI	228	85 frames/sec	1	1.9
AVIRIS	224	Variable (on demand)	20	0.4 to 2.5
FieldSpec Pro	2,151	Variable (on demand)	30	0.35 to 2.5
Polarimetric Radar	NA	NA	3 to 30	9.47 GHz
SAR	NA	NA	5	20 to 80 MHz
GLAS	NA	91	NA	0.532

* Except in the case of Polarimetric Radar and SAR, whose resolution is GHz and MHz, respectively.

Despite substantial progress made with this approach in the last decade, modeling and predicting wetland forest attributes remain a relatively little explored field of research (Proisy *et al*. 2007, Giri 2016). As early attempts in this direction, Lucas *et al*. (2007) and Simard *et al.* (2006) produced examples of mangrove attribute estimations based on remote sensing data acquired through active sensors: Advanced Land Observing Satellite/L-band polarimetric SAR (ALOS-PALSAR) and Ice, Cloud, and Land Elevation Satellite/Geoscience Laser Altimeter System (ICESat/GLAS). This early work delivered the foundations for a study that, to this date, continues to stand out as the most successful effort in the realm of wetland forest attribute modeling. This is the work of Proisy *et al*. (2007), who predicted biomass in mangrove forests of French Guyana. Their work relied on two novel theoretical and methodological contributions in modern remote sensing: the concept of image surface metrics and the FOTO (Fourier-based Textural Ordination) method to predict mangrove biomass based on very high-resolution (1 m) IKONOS imagery (Table 3).

Surface metrics quantify pixel spatial distribution and reflectance in an image and are closely related to landscape heterogeneity (McGarigal *et al*. 2009). Every pixel in a scene contains reflectance data for various wavelengths with valuable information on the structural composition of the surfaces (Haralik *et al*. 1973, Strahler *et al*. 1986, Woodcock & Strahler 1987, Shaw & Burke 2003). There are two types of surface metrics: (1) first-order or tonal metrics, calculated from the analysis of the reflectance recorded in individual pixels, and (2) second-order surface metrics, also known as textural metrics, calculated with the spectral values of at least two (but usually more) contiguous pixels (Haralik 1979).

Proisy *et al*. (2007)'s study represents the first successful attempt to predict mangrove biomass using high-resolution satellite imagery. From their work, relevant conclusions emerged, for example, regarding the optimal pixel window size for biomass modeling. For this reason, this work is an essential reference to study mangrove forests from a perspective based on the analysis of the spatial relationships of the components both in the images and on the terrain. The findings of this study triggered much research in many temperate (Block *et al*. 2016) and tropical (Couteron *et al*. 2005, Ploton *et al*. 2012, Solórzano *et al*. 2017) plant communities, including successional forests (Gallardo-Cruz *et al*. 2012). However, its impact on wetland forest studies is relatively modest. A notable exception is a study conducted by Solórzano *et al*. (2018), also based on high-resolution imagery and in the contrast of FOTO and GLCM (Gray Level Co-occurrence Matrix), two commonly used methods to analyze image texture. Despite the clear advantages of using these methodological tools for the accurate prediction of wetland forest attributes, recent studies continue to use tonal metrics and multiple regression as the basis for the prediction of forest attributes such as aboveground biomass and carbon stocks (Baloloy *et al*. 2018, Hu *et al*. 2020, Nguyen & Nguyen 2021). Therefore, the two approaches will likely continue to co-exist for some time.

Future challenges in the study of wetland forests through remote sensing

Notwithstanding the key conceptual and methodological developments achieved in the field of remote sensing focused on the study of mangroves and other wetland forests, the best-known aspect of these communities across the tropics continues to be their spatial distribution (Table 1). Indeed, wetland forests delimitation and mapping continue to be essential tasks that will allow us to evaluate as precisely as possible its territorial extent, loss, or expansion (Green *et al*. 1998b, Blasco *et al*. 1998, Sulong *et al*. 2002, Wang *et al*. 2019, Nguyen *et al*. 2021). Nonetheless, it is also true that remote sensing approaches have opened many possibilities of analysis previously unforeseen, and many of them are only now beginning to be fully appreciated.

Research on wetland forests through remote sensing has faced challenges that have sometimes caused biases in the type of studies conducted, mainly favoring the mapping of these ecosystems, leaving the quantification and modeling of their structural attributes on a second plane. The main challenge is the modeling of some wetland forests characteristics, such as the complex salinity-flooding relationship (Thom 1967, Semeniuk 1980, Tomlinson 1986), that distinguish them from terrestrial ecosystems (Chatziantoniou *et al*. 2017), along with the difficulty to discriminate wetland forests, particularly mangroves, from other adjacent forest types using satellite imagery and other remote sensing inputs (Gupta *et al*. 2018). Due to the complex and highly dynamic flooding regimes that characterize wetland forests, acquiring the reflectance information of the site from remote sensing inputs is challenging. This difficulty points to the need for new methodological approaches. A promising alternative is to combine active and passive sensors as an efficient way to provide a more accurate depiction of the physical characteristics of these communities (Aschbacher *et al*. 1995, Green *et al*. 1998a, Kushwaha *et al*. 2000, Fatoyinbo *et al*. 2008, Kovacs *et al*. 2008, Aslan *et al*. 2016), even though to this date these studies continue to rely more heavily on passive than on active sensors (Figure 3B). Additional alternatives for the study of wetland forests imply working at different scales because different sensors are likely to capture different aspects of their variation (Steenvoorden *et al*. 2023). Finally, it would be valuable to use existing indices or propose new and more exact methods to extract specific biophysical parameters (Wannasiri *et al*. 2013), such as reducing the exposed water surfaces for more accurate estimates of community attributes.

While numerous LiDAR-based studies have utilized aerial vehicles for terrain data acquisition, there has been a recent emergence of the use of Terrestrial Laser Scanning (TLS), involving sensors positioned on the ground (Fröhlich & Mettenleiter 2004, Liang *et al*. 2016). Recent studies have showcased the effectiveness of TLS technology in precisely quantifying biomass within intricate coastal wetland vegetation. For example, Owers *et al*. (2018) demonstrated a good match between TLS-derived estimates of mangrove biomass and conventional allometric techniques. Furthermore, the dependability of TLS is reinforced by 3D surface reconstruction models, resulting in comparable above-ground biomass estimates for mangroves.

The concept of nature-based coastal protection is gaining increasing traction as a promising, sustainable, and cost-effective strategy to mitigate the risks of coastal flooding (van Hespen *et al*. 2023). Wetland forests, with their remarkable wave-attenuating capabilities, play a significant role in this natural approach to flood defense. Moreover, the restoration of mangroves and other wetland forests not only enhances flood resilience but also catalyzes substantial economic growth (Debrot *et al*. 2022).

Wetlands play a pivotal role in disaster prevention, water quality improvement, and carbon storage. Given that remote sensing technology can guide restoration efforts, as well as surveillance and monitoring, especially through high-resolution platforms, such as IKONOS, Hyperion, QuickBird and PlanetScope (Table 3), we urge governments and international organizations to make greater investments in remote sensing-based research and to use it as a law enforcement tool for the protection of these threatened ecosystems.

Final remarks

The world of remote sensing is constantly growing. With the rapid development of remote sensing imagery, new approaches have emerged; undoubtedly, there are still some unresolved difficulties (Nasiri *et al*. 2022, Pan *et al*. 2022). Remote sensing-based studies of mangrove and other wetland forest communities have accomplished half a century of development. Despite such a long period of constant advancement, it is noteworthy that most studies in this field have focused on the delimitation and mapping of this ecosystem. Notably, current remote sensing studies of wetland forests also address new research questions with novel goals and aims. A limited but rapidly growing number of studies have aimed at modeling and predicting various wetland forest attributes, especially their biomass and three-dimensional structure. However, this type of research still represents a small fraction of all remote sensing-based studies focused on these ecosystems. The difficulty to accurately describe and predict community attributes in forests that possess such a complex physical structure will likely be overcome by using LiDAR and radar-based techniques (Darmawan *et al*. 2014, David & Ballardo 2015, 2016) and by increasing the use of machine learning and other automated information analysis processes (Mahdianpari *et al*. 2020, Yang *et al*. 2022, Pham *et al.* 2023).

Considering the critical conservation issues of wetland ecosystems (Kathiresan & Bingham 2001, Lee *et al*. 2014, Islam *et al*. 2014) in the face of global warming (Soares 2009, Sandilyan & Kathiresan 2012), the need to gather accurate and reliable information on these systems has become a matter of urgency. Modeling wetland forest attributes from remote sensing inputs promises to achieve this goal. However, the study of wetland forests through remote sensing is still in an early stage of development. In the future, we will undoubtedly witness conceptual and methodological progress that will enable us to surmount the challenges remaining to this date.

Acknowledgments

We are grateful to Marco Antonio Romero Romero and Abril Chávez for figure preparation. This paper is in partial fulfillment of the Programa de Doctorado en Ciencias Biológicas, Universidad Nacional Autónoma de México. The authors have no conflict of interest to declare.

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Associate editor: Arturo de Nova

Author contributions: DC conceived the study, performed a search of the literature, analyzed the information, and wrote the original draft; JL-P, analyzed information; JAG-C, analyzed information; JAM, conceived the study, and wrote the first draft. All authors discussed the reviewed information, contributed significantly to the manuscript, and approved the final version.

Supporting Agencies: Consejo Nacional de Ciencia y Tecnología (CONACYT), grant FORDECyT 273646, LANRESC 293354. Consejo Nacional de Ciencias y Tecnología (CONACYT), Ph.D. scholarship (CVU 508420).