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The current status, potential and challenges of remote sensing for large-scale mangrove studies

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ABSTRACT

Large-scale mangrove studies are pivotal for coastal forest restoration and climate change mitigation as evidenced by an alarming fact that globally mangrove has declined more than 30% in the last 50 years. Consequently, such a rapid decline leads to 10% of the additional carbon emissions due to global deforestation. Remote sensing plays an indispensable role in studying large-scale mangroves. However, the status and evolution of how remote sensing helps large-scale mangrove studies have not been reported. More importantly, the potential and challenges of such studies are yet unveiled. To bridge these gaps, we investigated the evolutions, drivers, and future directions for remote sensing large-scale mangrove studies through a comprehensive literature review. We disclosed four key major research topics: extent delineation, vegetation structure, species composition, and ecological processes. Large-scale mangrove studies are still in their infancy, therefore, does not present distinctively chronological transitions as revealed by their counterpart in conventional mangrove studies. Although hardware and software advancements have made it viable to carry out large-scale mangrove studies, it is still challenging to culminate them, owing to the insufficient field samples and fine-resolution remote sensing imagery. Moreover, we found that topics exclusive to mangrove forests, such as outwilling, are still unexplored and waiting for further investigation.

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1. Introduction

Mangrove forests are short trees or shrubs inhabiting the intertidal zones between approximately 30° N and 37° S latitude (Feller et al. 2010; Field 1999). They are considered critical guardians for soil conservation, nature protectors for coastal assets and economic activities, and beautiful landscapes for tourists (Alongi 2009, 2002; Walters et al. 2008; Spalding and Leal 2021). Equipped with high carbon sequestration rates, mangrove forests are also valuable carbon sinks (Bouillon et al. 2008; Spalding and Leal 2021). The carbon density of the mangrove ecosystem is four times that of tropical forests despite the fact that they only account for 0.4–7% of the total global carbon sink (Alongi 2020; Spalding and Leal 2021). Besides, mangrove forests are essential for coastal biodiversity (Cannicci et al. 2021; Feller et al. 2010; Walters et al. 2008). They support a significant

number of benthic invertebrates, fishes, wildlife animals, and microbiome, among which 341 species are vulnerable to endangerment (Spalding and Leal 2021; Feller et al. 2010). Thus, mangrove forests are invaluable for the global ecology and economy.

Large-scale mangrove observations, including studies at national, continental and global scales, are of paramount importance, owing to the unprecedented disturbance congregated by climate change and human activities in the tropical and sub-tropical coastal zones (Rivera-Monroy et al. 2017; Spalding and Leal 2021). Due to the erratic climate change and human activities at large scales, the degradation and deforestation of mangrove forests are inhomogeneous through space and time (Goldberg et al. 2020; Spalding and Leal 2021). From 1996 to 2016, global mangrove forests have witnessed a 4.3% net loss, the majority of which happened in South Asia (44.83% of the loss) (Spalding and Leal 2021). Without large-scale mangrove studies, we cannot have comprehensive knowledge of critical challenges confronted by mangrove forests, such as the distribution of deforestation hotspots, the most endangered species, and the extent of human and climatic threats. In addition, mangrove forest studies at or above a national scale are valuable references for mangrove protection and climate change resilience projects. Owing to the dramatic disappearance of global mangrove forests in the 20th century, mangrove conservation and restoration has become a critical issue for countries around the world. However, different approaches and stages are implemented among countries with different interests and attitudes to mangrove forests. For instance, the first mangrove reserve in China was established in 1976 while the first reserves in Philippines were not proclaimed until five years later, although both countries have had dramatic loss of mangrove forests in the last 50 years (Jia et al. 2018; Primavera and Morvenna a Esteban 2008). Additionally, replanting mangrove forests is taking place in numerous countries, since it is efficient in carbon sequestration with soil carbon accumulation rate 10 times that of temperate forests and 50 times that of tropical forests (Cui et al. 2018; Laffoley and Grimsditch 2009; Yee 2010). During the implementation of mangrove reforestation, appropriate mangrove policies and knowledge collected at national scale, including the suitable location, species, and replanting methods, are required (Sasmito et al. 2019; Adame et al. 2018; Feka 2015). In summary, large-scale mangrove studies, especially these at or above national scales, are dreadfully needed. Thus, in this paper, large-scale studies are defined as the studies implemented at national, continental, and global scales.

Remote sensing has been accredited as a prevalent method for large-scale mangrove observation. Large-scale mangrove studies based on field measurements are not only time-consuming and labour-intensive, but also inconsistent across space and time since data collection is difficult to synchronize and the standards of measurements are incompatible (Giri et al. 2011). Alternatively, remote sensing-based studies are able to derive timely and spatially continuous observations of the earth surface without going to the field, which significantly facilitates the data collection for large-scale studies. For instance, utilizing thousands of Landsat images, Giri et al. (2011) generated the first comprehensive and globally consistent mangrove distribution map for the year 2000, which is impossible to be implemented using conventional fieldwork. In addition, using ALOS PALSAR and Landsat, Bunting et al. (2022) generated the time-series global mangrove distribution maps for the first time. Besides distribution mapping, remote sensing observations also facilitated various analyses for large-scale mangrove forests, such as damage evaluation (Taillie et al. 2020), health evaluation (Chellamani, Prakash Singh, and Panigrahy 2014),

biomass estimation and species modelling (Nayak and Bahuguna 2001), by providing various spatially continuous observations.

Nevertheless, no existing reviews can satisfy our demands for a comprehensive understanding of large-scale remote sensing mangrove studies. The most relevant reviews are the ones about remote sensing for mangrove forests (Kuenzer et al. 2011; Heumann 2011; Wang et al. 2018). Spatial scales are not specified. Significant two of these reviews were made by Wang et al. (2019) and Worthington et al. (2020). Wang et al. (2019) presented the most comprehensive review of mangrove remote sensing for the last 60 years. Key milestones, drivers of the topic transition and future directions were identified and deliberated in depth based upon a total of 1207 publications published between 1956 and 2018. However, the great majority of these publications are at local scales. Although they pointed out that large-scale remote sensing is one of the future directions for mangrove studies, only 16 large-scale mangrove studies were cited in this review. In addition, Worthington et al. (2020) analysed the existing mangrove products and explored the connection between these products and policy actions. In this study, 21 existing and 7 upcoming global mangrove datasets were analyzed. However, using keyword search in Web of Science, we have found 79 large-scale mangrove studies, about one third of which were published after 2019. In addition, we found that national- and continental-scale studies were much more and developed much earlier than global studies in remote sensing (Figure 1), while they were barely summarized and analyzed. Moreover, since the availability of Google Earth Engine (GEE) in 2015, the number of large-scale mangrove studies is surging, which signals a rapid development in a foreseeable future (Figure 1). Nevertheless, what is required for the future is still unclear. Thus, to guide the future large-scale mangrove studies, a comprehensive large-scale mangrove review is required. To our knowledge, three gaps are still existing.

First, the current topics of large-scale mangrove studies are not unveiled in-depth. Research topics for these large-scale studies can be quite different from their counterparts

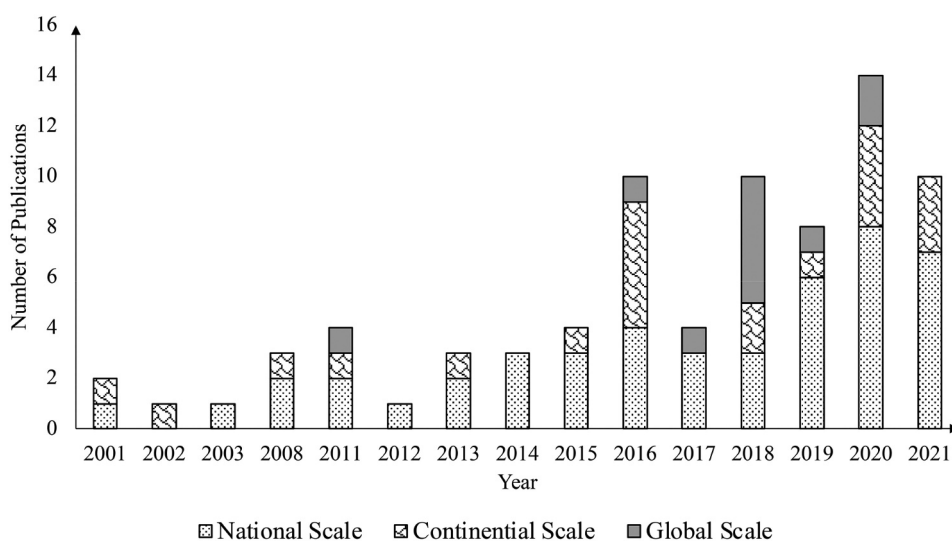


Figure 1. Large-scale mangrove literature with remote sensing.

for local scales and global scales. This is caused by the fact that large-scale studies aim to gain an overall understanding of mangrove forests, while local-scale studies intend to have a detailed analysis of mangrove forests under restricted geographic and environmental conditions. For instance, the significance of mangroves in preventing global warming is unique in large-scale studies and difficult to be discussed at local scales. In addition, compared with national-scale or continental-scale studies, global-scale studies require more data and stronger computation capabilities. Thus, the development of global mangrove studies can be quite different from that of large-scale studies. Wang et al. (2019) concluded that there are three major topics in mangrove forests: distribution mapping, biophysical parameters inversion, and ecosystem process characterization. Worthington et al. (2020) believed that there are three major types of global mangrove products: baseline products (such as mangrove extent and change), secondary datasets (such as mangrove fragmentation), and analyses of ecosystem services and biodiversity. However, whether and how these research themes happened in large-scale studies is still unknown. Without a specific understanding of the current large-scale mangrove studies, it will be difficult to analyse the evolution and the future directions in mangrove studies at large scales.

Second, the evolution of topics in large-scale mangrove research is not disclosed. It can be quite different from that for studies at pervasive scales. Computation capability and data accessibility are both significant for large-scale studies, while the increased temporal and spatial resolution of remote sensing images and the availability of SAR played an important role in traditional mangrove remote sensing (Wang et al. 2019). Additionally, although the topic evolution in global-scale mangrove studies may be comparable to that in large-scale studies, a detailed analysis of the evolution in global-scale studies is still missing. Therefore, a thorough review analysing the effect of both computation capability and data availability is still needed.

The third gap exists in the unforeseen future directions of large-scale mangrove studies. With the advancement of new remote sensing data, such as Landsat 9, Sentinel-1 and Sentinel-2 images with improved spatial and temporal resolutions, and the popularity of GEE, new opportunities have arisen for large-scale mangrove studies. Wang et al. (2019) predicted that with the availability of new data and the improvement of computation capability, local mangrove studies can be expanded to large or global scales. However, opportunities exclusive to large-scale mangrove study, e.g. the influence of mangrove forests on global climate change, are yet to be fully examined. Additionally, Worthington et al. (2020) believed that the improved satellite technologies have a high potential to make near real-time observations of mangrove forests. However, new topics driven by these technologies were not fully discussed. Thus, a comprehensive review of large-scale mangrove studies using remote sensing is in urgent demand. Without such a review, we cannot efficiently utilize the existing remote sensing data and platforms and answer the following two questions: (1) what is the status of current large-scale mangrove studies? (2) what are future directions and challenges?

Thus, we set aside three objectives: (1) to reveal the current status of large-scale mangrove studies (including national-, continental- and global-scale studies) by identifying key research topics; (2) to identify drivers for the evolution of these research topics; (3) to outline the potential and challenges of remote sensing in large-scale mangrove studies.

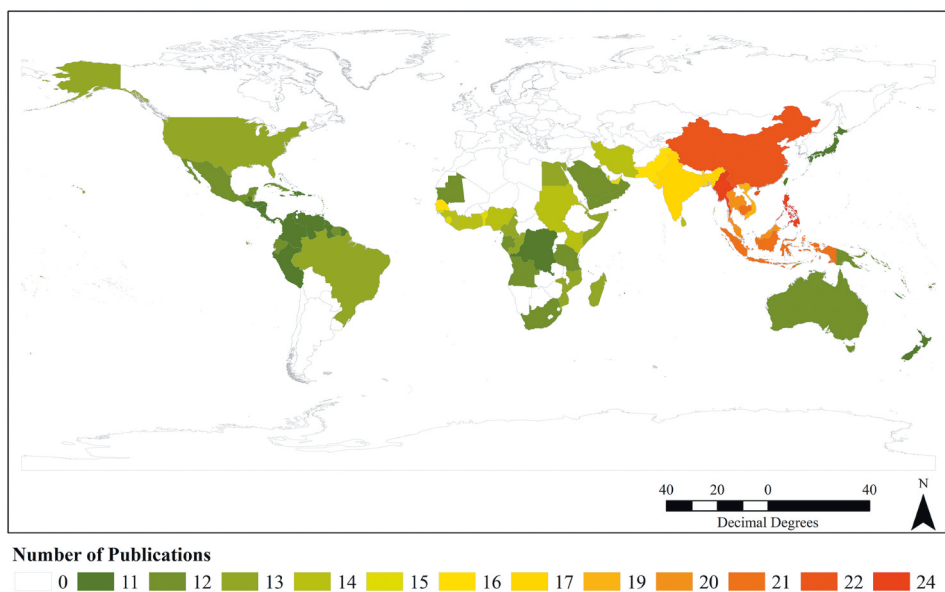


Figure 2. Number of remote sensing large-scale mangrove studies in each country.

2. Remote-sensing large-scale mangrove studies under topics

We carried out a comprehensive search of remote-sensing mangrove studies exclusively at large spatial scales (national, continental, or global scales). The Clarivate's Web of Science database was adopted with the most relevant keywords, such as 'mangrove' and 'remote sensing'. Then, we run a manual selection of publications that only fall in the large scales. Our search yielded 79 peer-reviewed journal articles. Coinciding with the fact that Asia maintains the largest extents of mangrove (42%) (Giri et al. 2011), a majority of our discovered large-scale mangrove studies caught out their research in Southeast Asia (50 out of 79) (Figure 2), highlighting the lack of knowledge and studies about large-scale mangroves in Africa, America, and Oceania.

We synthesized these large-scale mangrove studies into four major categorical topics by abiding the significant vegetation traits that can be extracted from the remote sensing data (Huylenbroeck et al. 2020): (1) Delineation, focusing on mapping the spatial distribution of mangrove forests; (2) Species composition, analysing the composition of mangrove forests, e.g. mangrove communities and species; (3) Vegetation structure, quantifying the physical characteristics of mangrove forests, such as density, height, and biomass; (4) Ecological processes, evaluating how mangrove plants accomplish the complex process of living. In Figure 3, the year of the first study for each sub-topic is plotted. In the following sections, we will discuss the evolution of these sub-topics under each topic.

2.1. Delineation

Large-scale mangrove delineation aims to trace the spatial distribution of mangrove forests. The national, continental and global mangrove maps, made from remote sensing

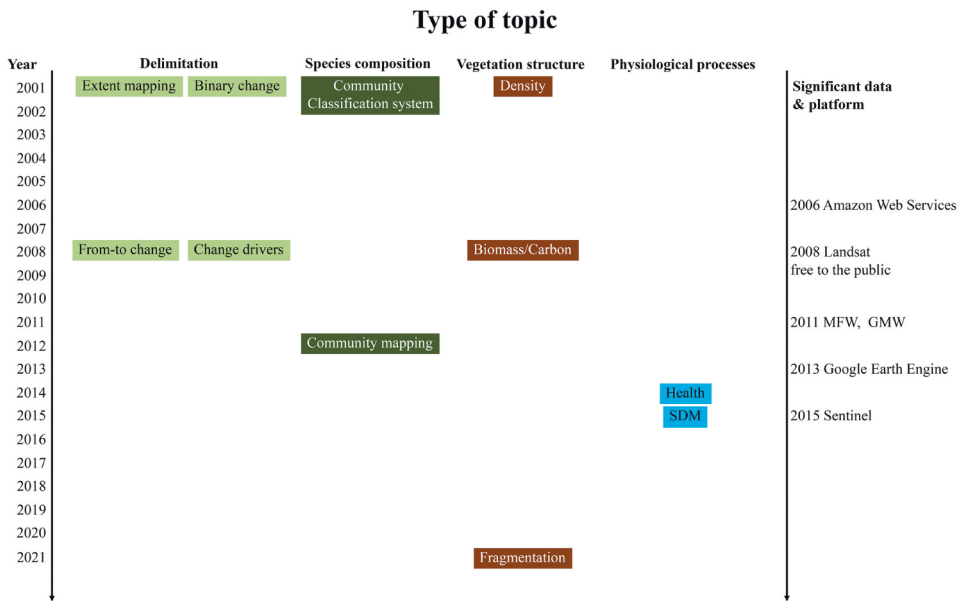


Figure 3. Evolution of remote sensing large-scale mangrove studies in remote sensing.

images, serve as a significant foundation for investigating various topics on mangrove forests at large scales, such as species composition, vegetation structure and ecological process. The history of large-scale mangrove delineation can be traced back to 2001. Until 2021, 53 significant mangrove delineation studies were found. They can be further classified into two sub-topics: extent mapping and change detection. In this section, we described the current studies on these two sub-topics separately.

2.1.1. Extent mapping

Large-scale extent mapping delineates the spatial boundaries of mangroves forests with remote sensing. It can be conducted either at a certain time point or at successive points in time. To our knowledge, it is the most productive sub-topic in remote sensing large-scale mangrove studies. Almost half of the delineation studies (25 out of 53) focused on extent mapping. Among them, two significant studies were made by Giri et al. (2011) and Bunting et al. (2018). The products made by these two groups, the Mangrove Forests of the World (MFW) (Giri et al. 2011) and the Global Mangrove Watch (GMW) (Bunting et al. 2022), were widely utilized and notably enhanced the mangrove studies at large scales. Extent mapping for large-scale mangrove forests can be summarized into two stages. Before 2015, visual interpretation is widely utilized, due to the lack of data and computation capability. After 2015, thanks to the availability of suitable remote sensing imagery, such as Landsat and Sentinel images, and cloud computing platforms, the automation of large-scale mangrove extent mapping was notably improved by using supervised classification methods.

To our knowledge, the first large-scale mangrove extent mapping publication with remote sensing was made by Blasco, Aizpuru, and Gers (2001). It is also the first time that remote sensing is applied in a large-scale mangrove forest investigation. The spatial

distribution of mangrove forests from West Bengal in India to Ho Chi Minh in Vietnam in tropical continental Asia was visually delineated from Système Pour l' Observation de la Terre (SPOT) 'quick look' images with 120-m spatial resolution. At last, based on the coverage of mangrove forests, their study areas were classified into eight categories: dense mangroves, leafless mangroves, mangrove deforestation areas, mangrove afforestation areas, degraded mangroves, very degraded mangroves, mangrove land partly converted to fish ponds, and mangrove land converted to agriculture. The extents of 6,900-km² mangrove forests in Myanmar were first delineated at a national scale. However, they conclude that it is difficult to delineate the exact areal extent of mangrove forests at large scales even with the help of remote sensing, since the spatial resolution of their data source is not fine enough.

Subsequently, the free and open policy of Landsat data in the year 2008 facilitated the remote sensing data collection for large-scale mangrove studies, which brought new opportunities for large-scale mangrove extent mapping. With the help of Landsat images covering the coastal zones around the world, the first comprehensive and globally consistent mangrove map for the year 2000 was generated by Giri et al. (2011). A hybrid supervised and unsupervised classification method was utilized to alleviate the workload of mangrove extent mapping at the global scale. Water bodies and inland areas, where mangrove forests were impossible to exist, were masked out in advance. After that, an unsupervised classification method, ISODATA, was utilized to segment the remaining areas into several homogenous regions, which significantly improved the efficiency of visual mangrove interpretation. By comparing their studies with existing global mangrove products, they found that most products overestimated the area of mangrove forests.

To improve the automation of large-scale mangrove extent mapping, numerous studies using supervised classification methods emerged after 2015. A representative supervised classification study for large-scale mangrove forests was made by Chen et al. (2017). They mapped the distribution of mangrove forests in China using time-series Landsat images in GEE. A phenology-based classification method was developed. Instead of using remote sensing images at a certain time point, they extracted phenology information from time-series Landsat images, which notably improved the accuracy of mangrove mapping. At last, the overall accuracy of their map is above 99%. They believe that, by facilitating the process of data preparation, GEE brings new opportunities for large-scale mangrove mapping. Another compelling study was proposed by Bunting et al. (2018). It was the first time a time-series database, the GMW, was created to monitor the distribution of global mangrove forests. They developed a two-iteration mangrove mapping method with a supervised classifier, the Extremely Randomized Trees classifier, and two remote sensing data sources, Advanced Land Observing Satellite data and Landsat imagery. The overall accuracy of their baseline for 2010 is 95.2%. The change detection in mangrove forests was significantly facilitated by this study.

2.1.2. Change detection

Change detection with remote sensing in large-scale mangrove studies is mainly focused on analysing the change in mangrove distribution. In the 1990s, mangrove forests witnessed a significant decrease caused by human activities and climate change. To timely monitor their distribution, studies of large-scale mangrove change detection emerged around 2000. Until 2021, we found 28 change detection studies.

Three typical sub-topics were investigated: binary change detection, identifying the locations where changes have happened without concerning the land cover types before and after the change; from-to change detection, labelling a certain pixel with land use and land cover types before and after the change; change driver detection, identifying factors that have caused the change of mangrove forests. However, in reality, there are no clear boundaries between the from-to change detection and the change driver detection in large-scale mangrove studies with remote sensing. For instance, the conversion of mangrove forests to agricultural land can be considered either a from-to change or mangrove loss caused by a factor, agriculture. Thus, to better trace the evolution of change detection in remote-sensing large-scale mangrove studies, we defined the from-to change detection as the change directly detected from remote sensing classification results, while the change driver detection cross-references the classification results and the measurements of change drivers.

2.1.2.1. Binary change detection. Binary change detection is popular in remote-sensing large-scale mangrove studies after the year 2008 when Landsat imagery became free to access. In total, we found 16 remote-sensing publications for binary change detection in mangrove forests at large scales. All of them, except the one made by Nayak and Bahuguna (2001), were made after 2013 and counted Landsat images as their primary data source. Red and Near Infrared bands were utilized the most. Additionally, all the 16 studies we found employed a post-classification change detection method. To detect the gain or loss of mangrove areas, time-series mangrove extent maps were produced using traditional remote sensing classification methods, such as visual interpretation, thresholding, and random forests.

The most-cited article is made by Kirui et al. (2013). Changes in mangrove extents in Kenya were estimated over the 25 years from 1985 to 2010. To detect the binary change, they produced four mangrove extent maps for the years 1985, 1992, 2000, and 2010, using Landsat images and a maximum likelihood classification algorithm in advance. Changed regions were delineated by comparing these resultant maps. They found that mangrove extents in Kenya lost 18% during the 25 years, while, at the same time, they admitted that bias may exist in their results, since mangrove forests with small patches or narrow strips are hard to be detected in the 30-m resolution Landsat images with the methods they utilized.

To improve the accuracy of mangrove change detection, deep learning is inventively applied by Guo, Liao, and Shen (2021) for the first time. They considered that deep learning is superior to traditional machine learning methods in extracting mangrove features from remote sensing images. Therefore, a deep learning method, Capsules-Unet, was applied to map the dynamics of mangrove extents in the 27 countries along the Maritime Silk Road from 1990 to 2015. At last, mangrove extents in 1990, 2000, 2010 and 2015 were successfully delineated with an overall accuracy from 86.9% to 88.7%. They found that about 21.5% of mangrove areas were lost during the 25 years.

2.1.2.2. From-to change detection. Until 2021, six large-scale publications were found on the from-to change detection with remote sensing. They considered that human conversions, e.g. converting mangrove forests to aquaculture and agriculture, were the major land cover changes in mangrove regions. To alleviate the workload in the from-to

change detection, almost all these studies were performed only in the changed regions which were delineated from binary change detection. Landsat imagery was the primary data source. The top two land cover land use classification methods they used are visual interpretation and random forests.

The first from-to change detection study was made by Giri et al. (2008) with post-classification change detection. Changed areas along a tsunami-affected coastal zone in Asia, including Indonesia, Malaysia, Thailand, Burma (Myanmar), Bangladesh, India, and Sri Lanka, were detected in Landsat images for the years 1975, 1990, 2000, and 2005. Then, the land use land cover conversions in these changed areas were visually interpreted. They found that about 12% of mangrove forests were lost from 1975 to 2005 in their study area, which is mainly caused by the conversion to aquaculture.

Subsequently, the time-series radar composite imagery was first utilized in mangrove change detection by Thomas et al. (2017). To identify the from-to changes, each mangrove region was visually interpreted in a mangrove distribution dataset, the GMW. At last, the changes in global mangrove forests were successfully detected with 89% overall accuracy, proving the feasibility of radar imagery in mangrove change detection. They found that, over the period from 1996 to 2010, there is no mangrove region staying away from the impact of human activities among which the most frequent one is the conversion of mangrove forests to aquaculture or agriculture.

Afterward, a significant work guiding future mangrove conservation action was proposed by Zanzo et al. (2021). They made a novel understanding of mangrove forests by predicting their future states. From-to changes from 1988 to 2019 were detected in the coastal area of Benin using Landsat imagery and the Maximum Likelihood Classification technique. Then, future trends of mangrove forests were predicted by 2050 with Markovian chain analysis. Conversion to grassland is observed as the major cause of mangrove loss from 1998 to 2019. Based on the projection of the future, they considered that mangrove forests in Benin will continue to decrease, while the speed is relatively slow.

2.1.2.3. Change driver detection. To facilitate the implementation of mangrove conservation and blue carbon projects, understanding the drivers of mangrove changes at large scales is important. From 2016, when the first study was published, to 2021, we found six remote-sensing studies on the change driver detection for large-scale mangrove forests. Each of them covers quite different subjects, ranging from the effects of global warming and sea-level rise (Giri and Long 2016), the social and economic processes underlying the change (Temudo and Isabel Cabral 2017; Fent et al. 2019), anthropogenic and natural factors for the loss of mangrove forests (Goldberg et al. 2020; Sakti et al. 2020), to the influence of water balance (Wilwatikta et al. 2020). The decision tree was the primary method they utilized. In addition, the Moderate Resolution Imaging Spectroradiometer data products (MODIS) with 250-m or 500-m spatial resolution, such as MOD13 and MOD16, were utilized as the major remote sensing data sources for two of the six articles we found, while the remaining four employed 30-m-resolution Landsat imagery. This may be caused by the factor that, with the implication of climate data at more than 5-km resolution, little difference will be made in the results if we only improve the resolution of optical images. In addition, the improvement will increase the workload in computation.

One of the significant remote sensing studies on the change driver detection was proposed by Temudo and Isabel Cabral (2017). They notably combined the quantitative binary mangrove maps with qualitative agricultural, environmental, and social information to uncover the historical, social, political and economic processes underlying the loss and gain of mangrove forests in Guinea-Bissau. Binary mangrove maps were delineated with Landsat imagery from 1990 to 2015, while the qualitative information was derived from fieldwork in more than 100 villages including informal conversations, group discussions, direct observation, and so on. They found that the conversion of mangrove forests to rice fields was the major cause of mangrove loss in Guinea-Bissau, although the conversion was obstructed by several factors, such as the war of Independence, years of drought, and inadequate policies.

In addition, the most cited work was done by Goldberg et al. (2020). They quantified the human and natural drivers for mangroves loss around the world from 2000 to 2016 with Landsat imagery. They believed that Landsat imagery alone was not capable of separating the five mangrove loss drivers they defined: erosion, commodities, settlement, non-productive conversion, and extreme weather events. Thus, they borrowed help from various products, such as the Global Forest Change 2016 water map, the Joint Research Centre Global Surface Water 2016 occurrence map, and the Global Human Settlements map. The results revealed that the primary drivers of mangrove loss are the conversion to aquaculture and agriculture. Southeast Asia is the hot spot of anthropogenic mangrove loss.

2.2. Species composition

Species composition described the presence of species in mangrove forests, which enables a detailed understanding of the species richness and ecosystem function of mangrove forests. It can be measured at a community level or a species level. For community-level studies, mangrove species are grouped into several categories according to their requirement for light, water, and soil (Franklin 1995; Ferrier and Guisan 2006). The characteristics of each category, e.g. distribution, are analysed. By contrast, species-level studies investigate each mangrove species separately. To our knowledge, there is no remote sensing large-scale mangrove study conducted at the species level by the end of 2021. Only four community-level studies are found. They can be divided into two stages: from 2001 to 2003, building community classification systems (Nayak and Bahuguna 2001; Murray et al. 2003), and from 2013 to 2015, making community maps (Bahuguna et al. 2013; Moore, Gilmer, and Schill 2015).

To the best of our knowledge, Nayak and Bahuguna (2001) made the first attempt in discovering the species composition of mangrove forests at large scales. They built a classification scheme for mangrove communities in India, referring to the field data, high-resolution images, and mangrove extent maps they made with Linear Imaging Self-Scanning System I and II data (LISS-I and LISS-II). However, a large-scale community distribution map failed to be generated, since the spatial resolution of LISS-I and LISS-II data is not fine enough to observe the difference between each community and the high-resolution images they have cannot cover all the coastal areas in India.

Additionally, a representative community mapping work at a national scale was caught out by Bahuguna et al. (2013). They reported a detailed mangrove inventory in each state

of India at a community level according to the geomorphological and ecological characteristics of mangrove species there. The distribution of these communities was delineated using the ISODATA classification method. Numerous remote sensing images with high spatial resolution were utilized: 23.5-m-resolution LISS-III data, 5.8-m-resolution LISS-IV data and 0.65-m-resolution QuickBird data. They found *Avicennia* and *Rhizophora* are the two dominant communities in India.

2.3. Vegetation structure

Vegetation structure describes the three-dimensional or the space arrangement of plants that controls their ecosystem properties, such as habitat suitability and ecosystem productivity (Ruiz-Jaén and Mitchell Aide 2005; Walter, Stovall, and Atkins 2021). To understand the stability of mangrove forests and their role in the global carbon cycle and biodiversity, vegetation structure studies at large scales are of great significance. In total, we found 18 remote-sensing studies focusing on three sub-topics: biomass estimation, density estimation, and fragmentation evaluation.

2.3.1. Biomass estimation

Large-scale mangrove biomass estimation measures the aboveground, belowground or soil biomass of mangrove forests. Since the publication of the first study in 2008, we found 10 studies under this topic. Aboveground biomass was estimated by most of them (nine out of ten). This is because after 2008, with the availability of mangrove distribution products at large scales, it is no longer a necessity to delineate a new map before estimating the biomass of mangrove forests. In addition, the Shuttle Radar Topography Mission (SRTM), which can directly describe the height of mangroves, is available. It is favoured by more than half of the studies, while the Landsat imagery is utilized by five studies. By contrast, only four belowground biomass studies and three soil biomass studies were found, owing to the incapability of remote sensing in penetrating the ground surface. Most of the belowground and soil biomass estimations were derived from multiplying a constant ratio to the aboveground biomass.

The most cited study of mangrove biomass estimation with remote sensing was proposed by Simard et al. (2019). Mangrove biomass in 2000 around the world was analysed. New allometric models were built to relate the aboveground biomass with mangrove canopy height maps derived from the calibrated SRTM. Published allometric models were carefully selected to obtain the belowground and soil biomass information from the resultant aboveground biomass. They concluded that the total carbon storage of global mangrove forests is around 5.03 Pg. In addition, considering the basal area can improve the accuracy in aboveground biomass estimation.

Moreover, Sanderman et al. (2018) published a representative study of mangrove soil biomass estimation with remote sensing. A significant harmonized mangrove soil carbon database was generated by compiling field data from peer-reviewed literature, grey literature, and unpublished data from several researchers and organizations. Then, a global soil carbon map of mangrove forests at 30 m resolution was generated using a novel machine-learning method. They found that the total suspended matter collected from Medium Resolution Imaging Spectrometer imagery and optical bands of Landsat imagery were significant predictor for soil carbon density.

2.3.2. Density estimation

Density is an important indicator of the nutrient and energy cycles in mangrove forests (Zhang et al. 2022). Under such a serious climate change and global human disturbance, large-scale density information, which can reveal the distribution, biodiversity and ecological function of all the mangrove forests, is an essential (Ashaari, Kamal, and Dirgahayu 2018). Five studies were found under this sub-topic. The three made before 2005 took help from visual interpretation. They classified mangrove forests into several density categories, e.g. sparse mangrove and dense mangrove. Then, visual interpretation was used to map the spatial distribution of these mangrove categories. By contrast, the two studies made after 2005 had less human intervention. Object-based image analysis, spectral unmixing algorithm and polynomial regression were utilized.

A notable study was made by Blasco and Aizpuru (2002). They classified the mangrove forests in the Bay of Bengal into six categories according to their density: Dense mangroves, degraded mangrove or young stands, very degraded mangrove or young stages, mangrove afforestation areas, active deforestation activities and mangrove areas converted to other uses. Various remote sensing images, e.g. SPOT and Resurs, were interpreted to generate mangrove density maps at a large scale. They found that the status of mangrove forests in different countries were quite different. For instance, the dense mangrove forests in India were degrading while the extents of mangrove forests in Bangladesh remained almost constant.

Another significant mangrove density study was made by Lymburner et al. (2020). They successfully measured the density of mangrove forests using a traditional biophysical canopy cover measure, Planimetric Canopy Cover Percent. Instead of making their own mangrove distribution map, the GMW made by Bunting et al. (2018) was utilized as a base map. The green vegetation cover fraction for each Landsat pixel in mangrove regions was derived using Landsat imagery and spectral unmixing algorithm. Then, the relationship between the fraction and the Planimetric Canopy Cover Percent were uncovered with third-order polynomial regression. For the first time, annual mangrove density (canopy cover) maps from 1987 to 2016 were created for Australia using Landsat imagery. They found that from 1992 to 2010 mangrove forests in Australia increased about 6% while from 2010 to 2017, more than 2% mangrove forests disappeared.

2.3.3. Fragmentation estimation

Fragmentation is the process of dividing a large land cover patch into several small parts (Wilcove 1986). It is a crucial element that determines the capability of mangrove forests in coastline protection and nutrient storage (Bryan-Brown et al. 2020). In 2021, the advancement of mangrove delineation enables the research on the fragmentation of mangrove patches at large scales with remote sensing. In total, we find two studies.

Gilani et al. (2021) analysed the mangrove fragmentation in Pakistan over the three decades from 1990 to 2020. Mangrove pixels in Landsat images were classified into four categories to evaluate the fragmentation: patch, edge, perforated and core. They revealed that the fragmentation of mangrove forests in Pakistan showed a decreasing trend, which means that mangrove tree canopy coverage is increasing there.

Zhang et al. (2021) measured the change of mangrove landscapes in China in 1987, 1990, 2000 and 2013 from four perspectives: area change, fragmentation, shape complexity and patch connectivity. Gaofen-1, ZY-3 and Landsat images were utilized as data

sources. They found that the area of mangrove forests had a decreasing trend before 2000. In addition, after 2000, although the area increased year by year, the fragmentation of mangrove patches is becoming more and more serious. Additionally, they concluded that it is difficult to do the fragmentation estimation using Landsat imagery only, since the medium-spatial-resolution images are too coarse to capture detailed shape information for mangrove forests.

2.4. Ecological processes

Ecological processes of mangrove forests include the species interactions, organism movements, nature disturbances and all the climatic, hydrological and biophysical processes happening in the forests (Bennett et al. 2009). They were investigated by 14 studies with remote sensing from two perspectives: Species distribution models (SDM) and health evaluation.

2.4.1. SDM

SDM aims to relate the occurrence or status of mangrove species with environmental characteristics. It highly relies on the availability of mangrove distribution data, mangrove health data, and environmental data. To our knowledge, SDM for large-scale mangrove forests was not investigated until 2016. Half of the existing ten SDM studies were published in 2020. It may be caused by the fact that the first consistent global mangrove distribution map, MFW (Giri et al. 2011), was not available until 2015. Currently, seven of the SDM studies derived the mangrove occurrence information from existing mangrove distribution products, such as the MFW and the Continuous Global Mangrove Forest Cover for the 21st century (CGMFC-21) (Hamilton 2016). Remote sensing images, such as MODIS and Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS), were widely utilized in describing the climate, topography, and vegetation characteristics of mangrove environment. However, soil data and human pressures were still hard to be measured using remote sensing. For existing studies, they were collected from in situ measurements or existing map products. Based on their objectives, existing SDM studies for large-scale mangrove forests can be divided into two categories: mangrove distribution prediction and suitable site estimation.

Mangrove distribution prediction aims to find the environmental factors impacting the distribution of mangrove forests. A representative study was made by Ximenes et al. (2016). They notably described the environment conditions for different mangroves species in Brazil using Self-Organizing Maps. The influence of 25 environmental parameters were analysed. They include 21 bioclimatic variables, three sea surface temperature derivatives, and salinity. Only the three sea surface temperature derivatives were collected from remote sensing data (Sensor Aqua-MODIS). All the others were from WorldClim database which was generated by interpolating weather station data. They revealed that different mangrove species have different tolerates for the environment. To be more specific, *Rhizophora harrisonii* and *Rhizophora racemosa* are sensitive to precipitation and aridity, while the others do not.

Suitable sites estimation evaluates the suitability of mangrove growing in a site, no matter it is occupied by mangrove forests or not, which can guide the mangrove rehabilitation and restoration strategies. A significant study was made by Syahid et al.

(2020). They developed land suitability maps for mangrove forests in Southeast Asian under different hydrodynamic, geomorphological, climatic, and socio-economic scenarios for both 2050 and 2070. A climate prediction data model was utilized to predict the future status of environment in their study areas. Notably, they made use of night light images, the black marble night-time light data, to evaluate the socio-economic activities in or near mangrove forests. In addition, Multi-Error-Removed Improved-Terrain DEM and CHIRPS data were utilized to derive topography and precipitation information. They found that currently, there is 398,000 ha of potentially suitable land for mangrove planting in Southeast Asia, and it will increase to 131,756 ha in 2070.

2.4.2. Health evaluation

Mangrove health has been evaluated by four studies at large scales. All of them reckoned the Normalized Difference Vegetation Index (NDVI) to be an effective index for health evaluation. One significant work was made by Chellamani, Prakash Singh, and Panigrahy (2014). NDVI collected from SPOT – Vegetation was used to classify mangrove forests in India into four health statuses based using thresholds. After correlating the health information with auxiliary data, they found that in major cities, climate change, human activities, and pollution were three major factors influencing the health of mangrove forests.

3. Key drivers for evolution

The evolution of topical transitions was primarily driven by the free access policy of Landsat data and the emergence of GEE, but not by domain requirements. Two milestones were present: Landsat in 2008 and GEE in 2015. Subsequently, three stages were present in large scale mangrove studies (Figure 4). The first stage is before 2008, followed by the second stage between 2008 and 2015. After GEE became popular in 2015, the third stage emerged. It should be noted that among the three stages, no distinctive topical transitions can be discerned whereas the evolution was largely driven by data availability

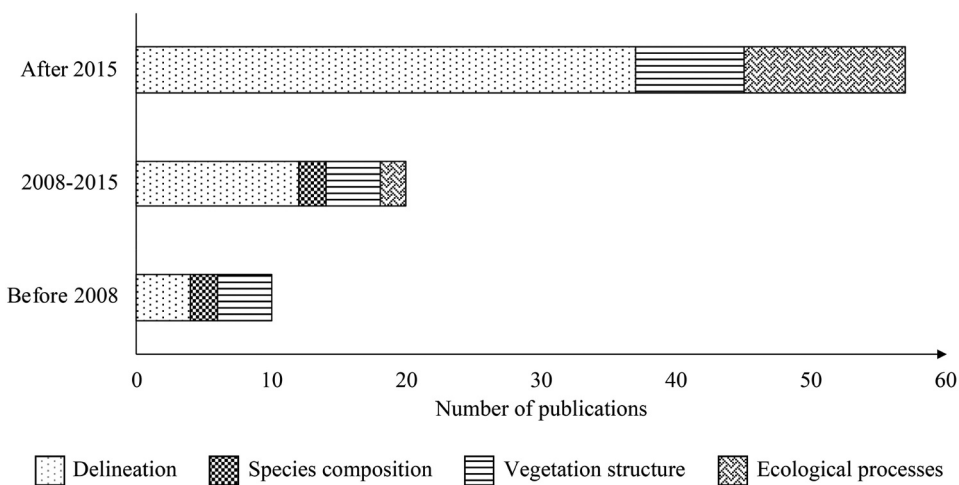


Figure 4. Topic evolution of remote-sensing large-scale mangrove studies.

and computational platforms. This is because large-scale mangrove studies are still in their infancy. It can be testified by the facts that almost all the existing large-scale mangrove studies brought their ideas from local studies. The main barrier for the reapplication is the lack of data and computational platforms. In the following, we discussed how the studies have been unfolded within each respective stage.

3.1. Before 2008, evaluating mangrove forests from multiple aspects

Before the year 2008, extracting everything they can from remote sensing images was the ultimate goal of all the four studies we found. This is because suitable remote sensing images were expensive during that time. Unlike terrestrial forests, most mangrove forests distribute as small and elongated patches which are difficult to detect under low spatial resolutions (Muchoney et al. 2000). However, prices for remote sensing images with medium spatial resolution, e.g. the Advanced Spaceborne Thermal Emission and Reflection Radiometer data (ASTER), Landsat and SPOT, were from 80 dollars to almost 7000 dollars per scene before 2008 (Wang et al. 2010). Tens to thousands of images are required for large-scale mangrove studies. Thus, the expensive data made it difficult to set up a study in mangrove forests at large scales. Thus, visual interpretation was employed in the four large-scale studies to make full use of the valuable images. Simplified characteristics of species composition and vegetation structure were all interpreted simultaneously when researchers delineated the mangrove extents referring to the colour, shape, texture, and tone of remote sensing images. That is the reason why the first delineation study, the first species composition study and the first vegetation structure study arise at the same time for mangroves at large scales. In summary, the time lag between the mangrove studies at local scales and studies at large scales is caused by the lack of affordable remote sensing imagery. Studies made before the opening of Landsat imagery have no specific research topic.

3.2. From 2008 to 2015, focusing on mangrove delineation

In 2008, the Landsat data free access policy stirred up a wave of using Landsat imagery in large-scale mangrove studies. About 65.28% studies made after 2008 utilized Landsat imagery as their data sources (Figure 5). The number of remote sensing large-scale mangrove studies quintupled by the end of 2015. Additionally, an expanding trend has been observed in the extends of their study areas. The first globally consistent map for mangrove forests and the first study for a nation with coastlines longer than 10,000 km were both made after 2008. In the meantime, the remote sensing large-scale mangrove studies started to be concentrated on one certain topic, which is distinctive from what happened before 2008. Mangrove delineation, aiming at building baseline maps for other topics, is the focal point. Among the 18 studies published from 2008 to 2015, there are 12 studies focusing on mangrove delineation.

However, due to the absence of powerful computing platforms, researchers reduced the requirement in computation at the expense of computational efficiency. To study mangrove forests at large scales, researchers should download, mosaic, and process tens to thousands of remote sensing images. Powerful computation capabilities are required for even a simple calculation. Thus, one-time observations, instead of time-series images,

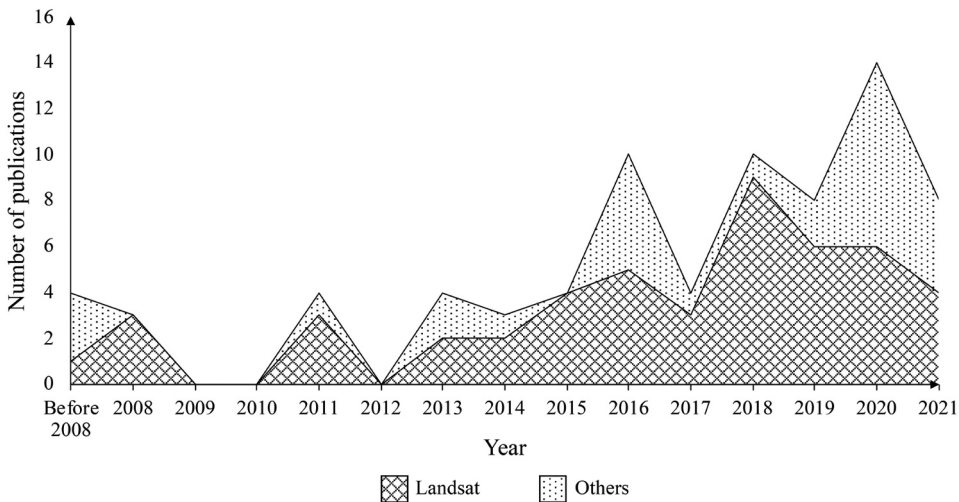


Figure 5. Literature using landsat images.

were carefully selected at a certain time point, generally during the dry season when the evergreen mangrove forests are distinctive from deciduous forests. The data size and the computational requirements for large-scale mangrove studies are decreased during this process. Besides, visual interpretation, capable of minimizing the computational requirements and ensuring high accuracy, is still the most popular method from 2008 to 2015. Until 2015, almost 55.56% of the existing remote-sensing large-scale mangrove studies are based on visual interpretation. Nevertheless, with too much human intervention, the time efficiency of these studies is difficult to keep pace with the rapid shrinking speed of mangrove forests. Therefore, the evolution of remote-sensing large-scale mangrove studies is waiting for a powerful computation platform before 2015.

3.3. After 2015, blooming with various topics

After 2015, large-scale mangrove studies with remote sensing burst out as the popularity of GEE, a powerful cloud computing platform consisting of numerous well-prepared remote sensing data, image processing functions and parallel cloud computing technology. Thanks to GEE, researchers can get rid of the tedious data preparing process and focus on their research questions. The time efficiency of large-scale mangrove studies is significantly improved. In 2021, 50% of them clearly indicate the adoption of GEE (Figure 6). Simultaneously, studies on mangrove delineation, vegetation structure and ecological processes increased 231.25%, 125.00% and 1300.00% correspondingly from 2015 to 2021.

The efficient and the automation of mangrove delineation at large scales are notably enhanced after 2015. Supervised classification methods start to be employed after popularity of GEE and the development of personal computers. There is no need for researchers to visually interpret everywhere in their study areas. Instead, as long as a classification model is developed with representative samples and effective classification algorithms, each pixel in remote sensing images can be labelled as mangrove or

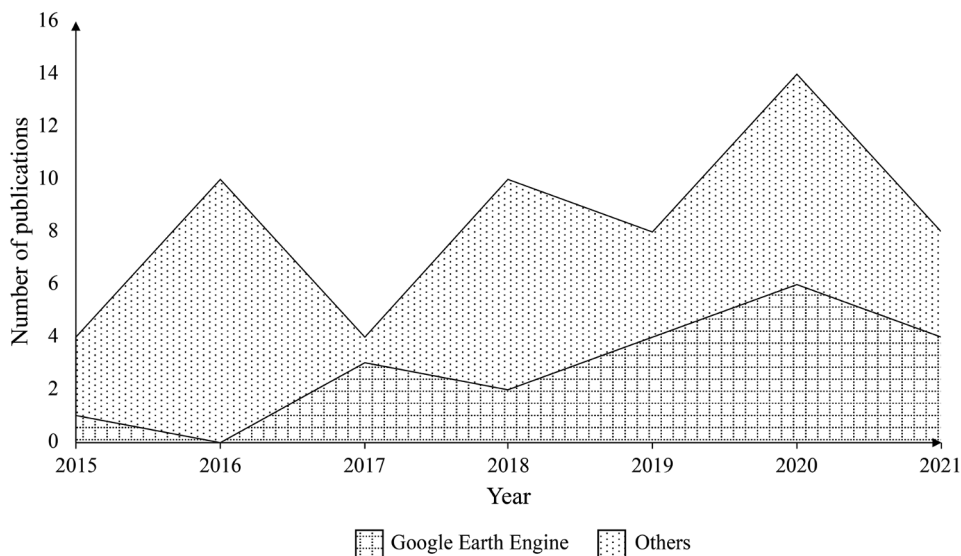


Figure 6. Literature using GEE.

other land cover types with little human intervention. Researchers can make mangrove maps at a low cost in time and labour. As a result, long-term and time-continuous measurements are enabled. Two representative products are the CGMFC-21 (Hamilton and Casey 2016) and the GMW (Bunting et al. 2022). By mapping the global distribution of mangrove forests annually at 30-m spatial resolution from 2000 to 2012, and from 1996 to 2016 respectively, they built a firm foundation for the further mangrove research. In summary, existing maps and technologies eased the way to obtain a large-scale base map for mangrove forests, which encourages researchers to further explore the characteristic of mangrove forests, such as the vegetation structure and ecological processes.

Additionally, the emergence of studies on vegetation structure and ecological processes is driven by both the GEE and the forest studies with remote sensing. As aforementioned, GEE ease the way to collect remote sensing data and to generate mangrove distribution maps at large scales. It built a significant foundation for large-scale mangrove studies. Additionally, referring to the forest studies with remote sensing, biological traits and functions of forests are crucial for a better understanding of the function and characteristics of forests. Leaf chlorophyll content and light use efficiency are the two widely investigated indexes in forest studies. However, currently, a thorough understanding of mangrove forests at large scales cannot be established, as the deficiency of ground truth and suitable remote sensing data. Under this circumstance, biological traits and functions of mangrove forests are only evaluated from the perspective of vegetation structure and ecological processes in recent 5 years. Existing resources, such as models built through fieldwork or local-level studies, are all utilized. Although the methodology here is simple and bias may exist, it is still a good start for the study of mangrove forests at large scales.

4. Future directions

Now that we have caught out a systematic review in [section 2](#) and [3](#), we realized that the future of large-scale mangrove studies should focus on the domain requirements. Current data- and platform-driven studies were empirical and largely based upon what is available: Remote sensing data and technologies were consistent with the ones widely used at local scales; Research topics were inspired by what have been done in local-scale studies. However, it is not enough. Only after knowing what are demanded, can we have a full understanding of mangrove forests at large scales, especially the knowledges exclusive to large-scale studies. From the perspective of remote sensing data and technologies, large-scale mangrove studies are both data-intensive and computation-intensive. Remote sensing data with large-area coverage and computation platforms with powerful computing capability are required. From the perspective of research topics, the role of mangrove forests in climate change, coastline protection and sustainable development can only be fully unveiled at large scales. Previously, no remote sensing study has touched upon these topics at large scales. It may be caused by two major factors: First, the lack of suitable data and powerful computation platform; Second, and importantly, the absence of such a throughout review specifically focusing on large-scale mangrove forests. Fortunately, new opportunities arose as the advancement in remote sensing data and technologies. In the following three sub-sections, we will share our thoughts on the gaps and potential research directions in two aspects: opportunities brought by the advancement in remote sensing and demand-driven topics for future studies.

4.1. *Emerging opportunities in remote sensing*

The advancement of remote sensing has created numerous opportunities for large-scale mangrove forests. They can be categorized into three aspects: (1) Improved automation in sample data collection; (2) Advanced remote sensing images; (3) Refined cloud computation platforms.

4.1.1. *Less human intervention in sample data collection*

Sample data play a key role in determining the quality of knowledges generated in large-scale mangrove studies. Samples are required to be adequate and representative to describe the inter- and intra-class variability for large-scale studies. Thus, majority of existing studies adopt field work and visual interpretation in sample collection, which is labour intensive and time consuming. Especially, after 2015 when Landsat is free and GEE is available, sample collection becomes the major cost in large-scale mangrove studies. Thus, to continuously monitor mangrove forests at large scales with affordable cost and high rate, new sample collection methods with less human intervention are under requirement. Two recent developments in automated sample extraction and data integration have the potential to bridge this gap.

Automatic sample collection is promising to significantly improve the efficiency of large-scale mangrove studies, especially mangrove delineation. To date, supervised classification methods are commonly used in mangrove delineation. Automatic sample collection can be a potential direction for timely mangrove extent mapping at large scales. Currently, there is only one automatic sample collection study for large-scale

mangrove mapping (Ying and Wang 2021). Thousands of mangrove training samples were automatically collected within two hours from historical mangrove products and time-series Landsat images. However, only mangrove samples can be collected using this method, which limits the classification method to one-class classification. Thus, with the availability of new remote sensing imagery and land cover maps, there is a high potential to further automate sample collection for land covers other than mangrove forests.

Data integration brings together the efforts of individual researchers, which considerably decreased the cost in sample data collection. Currently, innumerable local mangrove studies are available. For the year 2021, we found 1,416 mangrove studies in the Web of Science. Majority of them collected their own sample data. Although these data cannot support studies at large scales individually, the effect of their combination should not be ignored. Zheng et al. (2015) created a dataset of global wetland validation samples based on the publications they found in the Web of Science. This dataset includes 803 samples from 68 countries. Although these samples do not cover all the regions or countries around the world, it is still a good start to inspire us apply their methods in large-scale mangrove studies. Especially, numerous platforms are available now to facilitate the sharing of field data. For instance, the free online reference library for hyperspectral reflectance designed by Ferwerda, Jones, and Reston (2006) and the redesigned SPECCHIO system made by Hueni et al. (2009) are all great platforms for researchers to share their field measurements and to collaborate with each other in large-scale studies. In addition, besides the data collected by researchers or expertise, data collected by non-professional scientists, named citizen science data, are also valuable data sources. A great number of websites have been built to encourage the observations from volunteers, e.g. the National Phenology Network. However, mangrove field data or observations are still limited in these platforms. Thus, to facilitate potential large-scale mangrove studies, it is worthwhile to share the data from local studies in those platforms.

4.1.2. Advanced remote sensing images

The advanced remote sensing images are still underexploited in large-scale mangrove studies until 2022. As aforementioned, the Landsat optical images with 30-m spatial resolution and 16-day temporal resolution are the primary data source for current large-scale mangrove studies. However, they are too coarse to differentiate mangrove species and not informative enough to have detailed analysis on the sophisticated mangrove structure and ecological processes. That's the reason why mangrove delineation is the most advanced topic in large-scale mangrove studies while other topics are underdeveloped. Meanwhile, various advanced remote sensing images recording the reflectance, structure and environment information with high spatial and temporal resolution are available for almost all the earth's surface (Table 1). Nevertheless, they are not fully utilized in large-scale mangrove studies. Therefore, there is an urgent demand to exploit the applications of these advanced images.

Optical images with high spatial and temporal resolutions enable a comprehensive investigation on the phenology and the composition of mangrove forests at large scales. The Landsat 9, Sentinel-2, Planet and Gaofen images record the reflectance of the earth's surface for every 1 to 8 days with the spatial resolutions from 3 m to 10 m. Compare with Landsat 1–8, these images have higher time density and are more sensitive to the change of mangrove phenology. Vegetation fluctuation within 16 days, which is hard to be

Table 1. Advanced remote sensing images.

Information	Remote Sensing data	Spatial Resolution	Temporal Resolution	Type
Texture/reflectance	Landsat	30 m	8 days	Optical imagery
	Sentinel-2	10 m	5 days	
	Planet	3 m	1 day	
	GaoFen	4 m	4 days	
	Pléiades-1	2 m	1 day	
Structure	Sentinel-1	10 m	5 days	Radar
	ALOS PALSAR	25 m	44 days	
	Radarsat	1 m – 100 m		
	GEDl	25 m		
	ICESat-2 ATL08		91 days	
Environment	MODIS	250–1000 m	1–2 days	Temperature
	AVHRR	1.1 km	0.5 day	
	Sentinel-3	300 m	27 days	
	TRMM	5 km	16 times per day	Precipitation
	CHIRPS	0.05 degrees	daily, pentadal, and monthly	
	Sentinel-5P	7 km × 3.5 km	daily	Air quality Topography
	SRTM	30–90 m		
	ASTER	1 arc second		
	GDEM V3			
Future missions	Biomass	12 m	3 days	Biomass (SAR)
	FLEX	300 m	27 days	Fluorescence
	EarthCARE	285 m	25 days	Lidar

detected using Landsat 1–8, can be obtained now. For instance, phenology parameters, such as start of the season, the length of season, timing of the peak of season, and growth peak, can all be extracted from these time-series optical images using vegetation indexes (Celis-Hernandez et al. 2022; Shang et al. 2017). The major problem here may be the clouds that happen frequently in mangrove areas. Additionally, the advanced remote sensing images with high spatial resolution ease the analysis of mangrove species. Generally, mangrove species cluster as small patches, which are hard to be detected using medium-spatial-resolution images. Alternatively, high-spatial-resolution images, such as Pléiades-1 with 2-m resolution, have been proven successful in detecting artificial mangrove species at local scales (Wang et al. 2018; Pham et al. 2019). However, their effects at large scales are still unknown. Thus, it is worthwhile to explore the application of these high-spatial-resolution images in large-scale mangrove species monitoring. In summary, the advanced optical images with high spatial and temporal resolution are promising to improve our understanding of mangrove phenology and species composition.

In addition, the advanced Radar and Lidar images make it possible to have a detailed analysis on mangrove structure. Sentinel-1, the Advanced Land Observing Satellite-1 Phased Array type L-band Synthetic Aperture Radar data (ALOS PALSAR), Global Ecosystem Dynamics Investigation data (GEDl), Radarsat and the Ice, Cloud and Land Elevation Satellite-2 ATL08 product (ICESat-2 ATL08) are typical Radar or Lidar images monitoring the structure information of the earth's surface. Owing to their capability of penetrating clouds, Radar images are optimum complementary for optical images. In mangrove regions where clouds happen frequently, Radar images are the only reliable data with consistent and periodic records. Thus, their contribution in filling the cloud-caused data missing is significant. Additionally, Radar back-scatters are effective in detecting surface roughness and moisture content since they are sensitive to dielectric properties and geometric attributes. Therefore, Radar images

have a high potential to detect the change of mangrove structure and water content in mangrove forests under the unprecedented climate change, such as sea level rising and global warming. Moreover, Lidar images are promising to track the height of mangrove forests globally. Currently, mangrove heights in most large-scale studies were derived from SRTM which is made for the year 2000. Serious errors may happen when we use it for the years other than 2000. In summary, it is worthwhile to exploit the application of Radar and Lidar images in large-scale mangrove studies.

At last, remote sensing images are promising to successfully describe the environment of mangrove forests, such as temperature, precipitation, air quality and topography. Currently, plenty of environment data are collected from stationary measurements, such as WorldClim, which are not consistent in spatial. By contrast, remote sensing products can provide spatially continuous records which enable us to monitor inaccessible areas. However, only a few of them, e.g. MODIS and CHIRPS, are utilized in existing large-scale mangrove studies. The effectiveness of images with advanced spatial and temporal resolutions, such as Sentinel-3 and Sentinel-5P, are still waiting to be exploited. Thus, remote sensing environment data is promising to be widely used.

In summary, the advanced remote sensing images can provide diverse information which includes the reflectance or texture information from optical images, structure information from SAR images, environmental information from meteorological or topographical images. With the various remote sensing imagery, topics of large-scale mangrove studies is promising to become more diverse in a foreseeable future.

4.1.3. Refined cloud computation platforms

Thanks to the availability of cloud computation platforms, data collection and data processing are much more convenient for large-scale mangrove studies. Traditionally, a crucial challenge for large-scale studies is the tedious data collection and processing, due to the computational and storage limitation of desktop computers. To improve the efficiency of data processing, parallel execution comes out. It partially solves the problem. However, sophisticated computation and programming skills are required. Fortunately, nowadays, the user-friendly cloud platforms with numerous well-prepared remote sensing images and functions are available. They all provide strong cloud computational resources which considerably improve the efficiency of the heavy computation tasks in large-scale remote sensing. Thus, researchers can focus on their research questions with little concern about the limitation of their own devices. As a result, new opportunities arise.

Among the currently available platforms, GEE is the most promising for future application. As it is mentioned in [Table 2](#), GEE has the most comprehensive remote sensing datasets and more functions exclusive to remote sensing image process. The entire Landsat, Sentinel-1 and Sentinel-2 imagery are all embedded in it. In addition, besides basic machine learning algorithms, remote-sensing image preprocessing functions, such as image registration, are available. More importantly, after 2021, deep learning algorithms have been provided through its interaction with TensorFlow, which significantly broad the potential topics for future mangrove studies.

Table 2. Advanced remote sensing cloud computation platforms.

Cloud platform	Function services	Data services
GEE	From simple mathematical operations to advanced image processing and machine learning algorithms	The entire Landsat, Sentinel-1 and Sentinel-2, climate forecasts, land cover data and many other environmental, geophysical and socio-economic datasets
Amazon Web Services	Machine learning services	Landsat 8, Sentinel-1, Sentinel-2, China – Brazil Earth Resources Satellite programme, National Oceanographic, and Atmospheric Administration Advanced (NOAA) image datasets, global model outputs and open data supplied by DigitalGlobe with its SpaceNet challenges
Microsoft Azure	AI Tools	Landsat, Sentinel-2 products, and MODIS imagery
IBM PAIRS	Machine learning and AI	Landsat 7, Landsat 8, MODIS, and weather data from ORNL, ECMWF, NOAA, and so on

4.2. Demand driven evolution in large-scale mangrove studies

As aforementioned, new opportunities have been brought by the advanced remote sensing method, data, and platform. However, what is required in the future is still unknown. Without such a knowledge, it will be difficult for us to have a comprehensive understanding of mangrove forests at large scales. Thus, in the following sections, we analysed the demands with two steps. First, we discussed future opportunities brought by the advanced remote sensing technologies for monitoring mangrove forests. Second, we analyzed what can be done for discovering the role of mangrove forests in three questions of common interest: How to better understand the role of mangrove forest in global carbon cycle? What is the role of mangrove forests in coastline protection at large scales? What is relationship between mangrove forests and neighbouring communities?

4.2.1. Future opportunities in monitoring mangrove ecosystems at large scales

The importance of mangrove forests is not only represented by mangrove plants, but also the environment they live in. Thus, mangrove ecosystems, which consist of both the plants and the environment, are considered in this section. Currently, little has been done by remote sensing in monitoring them at large scales. Most knowledges we have now were derived from an assemblage of field works or local remote sensing studies. In the meantime, mangrove delineation is the only one topic that has been well-developed at large scales with remote sensing. Obviously, it is not enough. Spatially and timely consistent evaluation of mangrove ecosystems is under requirement, in order to keep pace with the rapidly, widely, and unevenly happened mangrove deforestation and degradation in recent decades. Fortunately, as the availability of advanced remote sensing technologies and data, new opportunities raised. As such, we share our insights on three key aspects: distribution, structure, and ecological processes.

4.2.1.1. Distribution. Although a great number of national, continental, and global mangrove distribution maps are available, challenges and opportunities still exist. We recognized that there are two major future directions for mangrove distribution at large scales: change drivers and species composition.

Change drivers are essential for mangrove protection and management. To date, all the six studies we found either focused on one specific change driver or analysed the change factors with a board classification system, due to the lack of suitable data source. Most of them brought help from field work and existing products, such as the Global Forest Change 2016 water map and the Joint Research Centre Global Surface Water 2016 occurrence map, since they believed that optical images alone were not capable of differentiating mangrove loss drivers effectively. Nevertheless, field work, as is known, is time-consuming and labour-intensive, especially when we applied it at large scales. Alternatively, using existing products limited the updating period of mangrove research, since studies can only made when the products are available. Fortunately, various environment images and Radar images with high spatial and temporal resolutions are available now. The water content and meteorological data can all be derived from remote sensing images. They are promising to not only replace the role of field work and existing products, but also help in making a comprehensive analyze on change drivers.

Species composition is under-developed in mangrove mapping studies. Due to the lack of suitable data and a powerful platform, most large-scale studies utilized visual interpretation to classify mangrove forests into several sub-classes according to their spectral reflectance. By contrast, it is proven by Wang et al. (2004) that time-series metre-level satellite imageries, such as, IKONOS with 4-m resolution and QuickBird with 2.8-m resolution, performed well in distinguish mangrove species at local scales with supervised classification methods. However, these two kinds of images are expensive to be applied at large scales. In addition, the frequently happened clouds are a significant issue for large-scale mangrove studies using optical images. Fortunately, Planet images and Sentinel-1 images open a new opportunity. The Planet images have 3-m spatial resolution and 1-day temporal resolution. For non-commercial research purposes, researchers can freely download up to 5,000 square kilometres of images every month from the Planet website. Additionally, the Sentinel-1 images are Radar images free of the cloud interference. They are demonstrated to be an effective complementary for optical images to limit the influence of clouds in mangrove mapping. Thus, mangrove species composition is promising to be exploited with Plante and Sentinel-1 images in the future.

4.2.1.2. Structure. The structures of mangrove forests have a close relationship with their ecological functions. They can be evaluated through biomass, leaf area index (LAI), and so on. However, little is known for them at large scales.

Existing mangrove biomass studies are mainly focusing on aboveground biomass estimation. Compared to studies in other ecosystems, remotely sensed biomass studies in mangrove forests were rarely conducted. There are two major shortages: the commonly used empirical model may cause large errors in the aboveground estimation; below-ground and soil biomass estimation needs further investigation. For existing studies, the aboveground biomass of large-scale mangrove forests is estimated using established empirical models and tree height data derived from SRTM. It is assumed that, with the same height, two mangrove plants will have the same aboveground biomass. However, it is not real. If the two plants belong to different species, their aboveground biomass should not be the same. In addition, SRTM is only available for the year 2000. For the years other than 2000, the utilization of SRTM may cause large errors. Thanks to the advanced remote sensing images, new opportunities arise. The Planet images open a new

opportunity in estimating the species composition of mangrove forests. Thus, the biomass of each mangrove species can be estimated separately. In addition, Lidar images and Radar images are capable of consistently providing tree height information for mangrove forests. Thus, the aboveground biomass estimation can be remarkably improved with the advanced remote sensing images. However, we should admit that the belowground biomass estimation in mangrove forests is still waiting to be improved. As the lack of in-situ measurements, a constant ratio provided by the Intergovernmental Panel on Climate Change guideline was utilized to derive belowground or soil biomass information from the above ground biomass products. Although it offers us a general view of mangrove biomass at large scales, a lot of in situ data is still required to improve the accuracy of belowground biomass estimation.

Additionally, LAI, which means half the total leaf area per unit ground surface area, is an important indicator for mangrove carbon sequestration. However, it has not been investigated in large-scale mangrove studies. For local studies, optical, Radar and Lidar remote sensing have been extensively used in LAI estimation for mangrove species. For instance, it has been tested that the LAI of black mangrove forests have strong correlation with Radar images (Kovacs et al. 2013). Thus, we believed that with advancement in mangrove species composition research, the LAI of mangrove forests has a high probability to be investigated in the future.

At last, almost all the established mangrove density studies classified mangrove forests in their study areas into several discontinuous density levels, such as low density and high density, using visual interpretation. The standards defining these levels are not uniform in different studies. To offer a continuous estimation for the density of mangrove forests, we suggested using spectral unmixing technologies in remote sensing. In addition, with the availability of high-spatial and high-temporal remote sensing images, the density of mangrove forests has a high probability to be estimated as a continuous variable.

4.2.1.3. Ecological processes. Ecological processes of mangrove forests represent both the capability of element exchange within mangrove ecosystem and the element exchange between mangrove forests and other communities. These processes are influenced by the health, environment, and phenology of mangrove ecosystems. To have a comprehensive understanding of mangrove forests, these factors are of great importance.

Large-scale mangrove health estimation is still at the initial stage. Only four studies using the NDVI index to evaluate the health of mangrove forests in India is found. Two gaps are existing. First, whether NDVI can be used to evaluate mangrove health at large scales is unclear. As mangrove species have different phenological phases and are unevenly distributed globally, it is difficult to find a uniform NDVI threshold to separate the healthy mangrove species from the unhealthy ones. Thus, an index considering the inhomogeneity between species is required for future studies. Second, the health of mangrove forests is a summary of numerous aspects, such as the health of leaves, structures, and fragmentation. Instead of using a simple index focusing on the photosynthesis ability of mangrove forests, such as NDVI, a comprehensive estimation of mangrove forests is waiting to be established. A local study made by Razali, Ainuddin Nuruddin, and Lion (2019) may offer us some ideas. They estimated the forest health using in situ measurements of the diameter at breast

height, seedling counting, rubbish observation, and the distance between the plots and the walkway and to the sea. For large-scale studies, tree height, photosynthesis capability, fragmentation of mangrove regions, distance to the walkway and distance to the sea can all be derived from the advanced remote sensing images. Thus, a comprehensive evaluation of the mangrove health at large scales is waiting to be established.

In addition, a unique characteristic of mangrove environment is tides. Their energy, temperature and salinity are significant for the ecological processes in mangrove forests. The energy of tides affects the nutrient exchange between mangrove forests and the ocean (Adame and Lovelock 2011). Temperature and salinity are important environment factors determine the distribution and species composition of mangrove forests (Noor et al. 2015). To date, three remote sensing studies testing the influence of temperature were found for large-scale mangrove forests. Remotely sensed temperature data derived from Sensor Aqua-MODIS were proven to be effective. However, to the best of our knowledge, no remote sensing studies has been established to test the influence of energy and salinity at large scales. Thus, to have a better understanding of tides in mangrove forests, it is worthwhile to exploit the potential of remote sensing in evaluating their energy and salinity. Thanks to the development of ocean satellites, the energy of tides can be evaluated by the strength, frequency and extent of flood tides collected from remote sensing data, e.g. sea surface topography and ocean circulation collected from TOPEX/Poseidon, Jason-1, OSTM/Jason-2 and Jason-3. In addition, according to the study of Mazda, Kanazawa, and Wolanski (1995), the more friction exists in mangrove forests, the superior the effects of ebb tides will be. Thus, the geomorphology of the mangrove ecosystem, such as elevation, slope and species composition, derived from exiting advanced optical, Radar and Lidar images, can also help in evaluating the energy of tides. Moreover, assessing the salinity of tides is enabled at large scales by the launch of satellites with L-band radiometer. For instance, the Soil Moisture and Ocean Salinity from the European Space Agency and the Aquarius from the National Aeronautics and Space Administration can all monitor the sea surface salinity at a global scale at weekly to monthly temporal resolution. Therefore, the status of tides has a high potential be analysed at large scales using remote sensing images. As a result, the changes in mangrove forests, such as biomass, can be better explained by considering the influence of tides.

At last, SDM is a popular method in remote sensing to discover the relationship between mangrove forests and their environment. However, existing SDM studies are all established at coarse spatial resolutions since climate variables are collected with low spatial resolution. Climate variables, such as temperature, can be evaluated at coarse spatial resolutions since they change slightly within a long distance in spatial. However, variables that change dramatically through space, such as water availability, will be underestimated at coarse spatial resolutions since the precise changes they made are lost during the aggregation process upscaling high-resolution data to low-resolution variables. Therefore, it is suggested to use the advanced Radar images to measure the water content in mangrove ecosystem. In addition, developing SDM with multi-scale factors is recommended (Mackey and Lindenmayer 2001). Models with hierarchical structures incorporating different predictors is worth being tested in large-scale mangrove studies.

4.2.2. How to better understand the role of mangrove forest in global carbon cycle?

Mangrove forests are of great significance in global carbon cycle, owing to their large carbon stock. However, their effect on the global carbon cycle is of great uncertainties for future climate, owing to the critical deforestation and degradation happening in mangrove forests since 20th century. To project the climate in the future, we need to have a comprehensive understanding of the mechanisms controlling mangrove carbon cycle. Here, we summarized that remote sensing can help in two aspects: estimating carbon sink efficiency of mangrove forests and evaluating the change of mangrove forests.

Photosynthetic capacity of mangrove forests is a pivotal component determining the carbon sink efficiency. It can be evaluated by biological traits, such as leaf chlorophyll content, leaf nitrogen content, light use efficiency and fluorescence. In traditionally studies, these traits are directly collected in the fields. Considerable time and labour are required even for the studies at local scales. Needless to say, it is almost impossible to be applied in large-scale studies. Thanks to remote sensing technologies, we found that these biological traits have a significant relationship with the structure of mangrove forests and the environment in mangrove ecosystems which can be detected through reliable satellite measurements. Forest structure indexes, such as LAI, biomass and tree height has been used to evaluate the carbon sink of terrestrial forests since 1981. For instance, Chen et al. (2019) successfully evaluated the global carbon sink of terrestrial forests through the status of LAI, CO₂ fertilization, nitrogen deposition, and climate information derived from various remote sensing images and stationary data. Their methods have a high potential to be applied in mangrove forests. We believe, with satellite meteorological data such as temperature and precipitation, we will be able to simulate the changes of these biological traits in mangrove forests.

Anthropogenic disturbances and climate change are the two major drivers of carbon loss in mangrove forests. From 1996 to 2016, approximately 60% of the global loss of mangrove forests are caused by human activities and 38% caused by climate change. For different drivers, the flow of carbon is different in mangrove forests. For instance, the mangrove clearance for charcoal will release the captured carbon directly into the atmosphere. By contrast, the sea level rising changed the mangrove forests through burying or submerging mangrove plants. The carbon released to the atmosphere is relatively less than that caused by mangrove clearance for charcoal. More importantly, the economic globalization and climate change have expanded the scale of mangrove loss to a global issue. Thus, in order to efficiently analyse the carbon flow in mangrove forests, it is of great importance to figure out driving factors for the loss at large scales. With the advanced remote sensing technologies, we believe the influence of anthropogenic disturbances and climate change will be estimated accurately in a foreseeable future.

4.2.3. What is the role of mangrove forests in coastline protection at large scales?

One of the significant services of mangrove forests are protecting coastal properties from waves and storms caused by hurricanes. However, no remote sensing research has been established in discovering the role of mangrove forests in coastline protection at large scales. In addition, it has been proven that only large-scale mangrove conservation efforts can effectively improve protection efforts (Valle et al. 2020). Thus, in order to guide the conservation of mangrove forests for coastline protection, large-scale studies are

required. We consider that remote sensing can help in two aspects: the evaluation of hurricane strength and the evaluation of property loss.

The strength of waves and storms are key factors represent influence of a hurricane. However, evaluating or quantifying these factors are difficult. Traditionally, these data came from the field observations. It is labour intensive and inconsistent in spatial and temporal. Thanks to the development of remote sensing, the wind energy can be recorded consistently. For instance, Blended Sea Winds offers the wind speed every six hours at 0.25-degree resolution. In addition, the process and extent of storm surges are influence by coastal topography which can be derived from SRTM or Lidar images. Thus, we believed that equipped with tide gauge data, spatial inundation model at different water levels can be built with remotes sensing images. Thus, remote sensing can provide remarkable help in the evaluation of hurricane strength.

Additionally, the loss of coastal properties after a hurricane is a significant indicator for the role of mangrove forests in coastal protection. Although we cannot measure the casualties with remote sensing, the loss of buildings, forests or other land covers can all be detected using change detection with optical images or Radar images. In addition, the night-time light remote sensing was proven to be effective in estimating the change of economic activities caused by hurricanes (Valle et al. 2020). Therefore, with the availability of advanced images, the role of mangrove forests in coastline protection is promising to be investigated in the future.

4.2.4. What is relationship between mangrove forests and neighbouring communities?

Mangrove forests and their neighbouring communities connect with each other through element and nutrient exchange. The major way they used is outwelling and tides. Outwellings are the materials, such as water-air co₂, Nitrogen/Phosphorus and organic matters, that mangrove forests output to the adjacent communities. They are considered nutrient subsidies for offshore creatures. However, no unified conclusion has been made on the role of these outwellings, due to the lack of data. The amount and the direction of material flows are determined by the strength and range of tides, and the geomorphology of tidal basins and mangrove forests. Thus, in traditional ecology studies, in-situ outwelling data are required for each location with different characteristics. Thanks to remote sensing technologies, the frequency and the strength of tides, DEM, waterway, and frictions of mangrove forests can all be quantified consistently in spatial and repeatedly in temporal. Therefore, equipped with a relatively small amount of in-situ outwelling data, there is a high potential to generate large-scale mangrove outwelling maps by building models between the remotely sensed data and the in-situ outwelling data. Moreover, the health and distribution of adjacent land covers can also be evaluated using remote sensing. Therefore, the effects of mangrove outwellings are promising to be analysed using remote sensing.

5. Conclusions

This review article identified four major topics in large-scale mangrove studies using remote sensing: delineation, species composition, vegetation structure, and ecological processes. The evolution in these topics is stimulated by the availability of remote sensing

images at large scales and suitable computation platform. In addition, the future directions are discussed deeply. We found that large-scale remote sensing mangrove studies are quite different from local-scale studies. Instead of coming out in chronological order, no significant time lag is observed among the four major topics regarding the emergence of new sub-topics. In addition, the large-scale studies are at the initial stage. Except for mangrove delineation, studies under the other three major topics are still repetitions of local studies in larger study areas. The future of mangrove forest studies should focus on the domain requirements.

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References

- Adame, M. F., C. James Brown, M. Bejarano, J. Alfredo Herrera-silveira, J. B. K. Paula Ezcurra, and R. Birdsey. 2018. "The Undervalued Contribution of Mangrove Protection in Mexico to Carbon Emission Targets." *Conservation Letters* 11 (4): e12445. doi:10.1111/conl.12445.
- Adame, M. F., and C. E. Lovelock. 2011. "Carbon and Nutrient Exchange of Mangrove Forests with the Coastal Ocean." *Hydrobiologia* 663 (1): 23–50. doi:10.1007/s10750-010-0554-7.
- Alongi, D. 2002. "Present State and Future of the World's Mangrove Forests." *Environmental conservation* 29 (3): 331–349. doi:10.1017/S0376892902000231.
- Alongi, D. 2009. *The Energetics of Mangrove Forests*. Germany: Springer Science & Business Media.
- Alongi, D. 2020. "Global Significance of Mangrove Blue Carbon in Climate Change Mitigation." *Sci* 2 (3): 67. doi:10.3390/sci2030067.
- Ashaari, F., M. Kamal, and D. Dirgahayu. 2018. "Comparison of Model Accuracy in Tree Canopy Density Estimation Using Single Band, Vegetation Indices and Forest Canopy Density (Fcd) Based on Landsat-8 Imagery (Case Study: Peat Swamp Forest in Riau Province)." *International Journal of Remote Sensing and Earth Sciences* 15 (1): 81–92. doi:10.30536/j.ijreses.2018.v15.a2845.
- Bahuguna, A., H.B. Chauhan, K. Sen Sarma, S. Bhattacharya, C. P. Subhash Ashutosh, T. Thangaradjou, L. Gnanppazham, V. Selvam, and S. R. Nayak. 2013. "Mangrove Inventory of India at Community Level." *National Academy Science Letters* 36 (1): 67–77. doi:10.1007/s40009-012-0087-x.
- Bennett, A. F., A. Haslem, D. C. Cheal, M. F. Clarke, R. N. Jones, J. D. Koehn, P. Sam Lake, L. F. Lumsden, I. D. Lunt, and B. G. Mackey. 2009. "Ecological Processes: A Key Element in Strategies for Nature Conservation." *Ecological Management & Restoration* 10 (3): 192–199. doi:10.1111/j.1442-8903.2009.00489.x.
- Blasco, F., and M. Aizpuru. 2002. "Mangroves Along the Coastal Stretch of the Bay of Bengal: Present Status." *Indian Journal of Geo-Marine Sciences* 31: 9–20.
- Blasco, F., M. Aizpuru, and C. Gers. 2001. "Depletion of the Mangroves of Continental Asia." *Wetlands Ecology and Management* 9 (3): 255–266. doi:10.1023/A:1011169025815.
- Bouillon, S., A. V. Borges, E. Castañeda-moya, K. Diele, T. Dittmar, N. C. Duke, E. Kristensen, S. Y. Lee, C. Marchand, and J. J. Middelburg. 2008. "Mangrove Production and Carbon Sinks: A Revision of Global Budget Estimates." *Global biogeochemical cycles* 22 (2). doi:10.1029/2007GB003052.
- Bryan-Brown, D. N., R. M. Connolly, D. R. Richards, F. Adame, D. A. Friess, and C. J. Brown. 2020. "Global Trends in Mangrove Forest Fragmentation." *Scientific reports* 10 (1):1–8.

- Bunting, P., A. Rosenqvist, L. Hilarides, R. M. Lucas, and N. Thomas. 2022. "Global Mangrove Watch: Updated 2010 Mangrove Forest Extent (V2. 5)." *Remote Sensing* 14 (4): 1034. doi:[10.3390/rs14041034](https://doi.org/10.3390/rs14041034).
- Bunting, P., A. Rosenqvist, R. M. Lucas, L.-M. Rebelo, L. Hilarides, N. Thomas, A. Hardy, T. Itoh, M. Shimada, and C. Max Finlayson. 2018. "The Global Mangrove Watch—a New 2010 Global Baseline of Mangrove Extent." *Remote Sensing* 10 (10): 1669. doi:[10.3390/rs10101669](https://doi.org/10.3390/rs10101669).
- Cannicci, S., S. Yip Lee, H. Bravo, J. Ricardo Cantera-Kintz, F. Dahdouh-Guebas, S. Fratini, M. Fusi, P. J. Jimenez, I. Nordhaus, F. Porri, Diele, K. 2021. "A Functional Analysis Reveals Extremely Low Redundancy in Global Mangrove Invertebrate Fauna." *Proceedings of the National Academy of Sciences* 118(32): e2016913118. doi:[10.1073/pnas.2016913118](https://doi.org/10.1073/pnas.2016913118).
- Celis-Hernandez, O., M. Villoslada-Peciña, R. D. Ward, T. Fernandes Bergamo, R. Perez-Ceballos, and M. Patricia Girón-García. 2022. "Impacts of Environmental Pollution on Mangrove Phenology: Combining Remotely Sensed Data and Generalized Additive Models." *The Science of the Total Environment* 810: 152309. doi:[10.1016/j.scitotenv.2021.152309](https://doi.org/10.1016/j.scitotenv.2021.152309).
- Chellamani, P., C. Prakash Singh, and S. Panigrahy. 2014. "Assessment of the Health Status of Indian Mangrove Ecosystems Using Multi Temporal Remote Sensing Data." *Tropical Ecology* 55 (2): 245–253.
- Chen, J. M., W. Ju, P. Ciais, N. Viovy, R. Liu, Y. Liu, and X. Lu. 2019. "Vegetation Structural Change Since 1981 Significantly Enhanced the Terrestrial Carbon Sink." *Nature Communications* 10 (1): 1–7. doi:[10.1038/s41467-019-12257-8](https://doi.org/10.1038/s41467-019-12257-8).
- Chen, B., X. Xiao, X. Li, L. Pan, R. Doughty, J. Ma, J. Dong, Y. Qin, B. Zhao, and Z. Wu. 2017. "A Mangrove Forest Map of China in 2015: Analysis of Time Series Landsat 7/8 and Sentinel-1A Imagery in Google Earth Engine Cloud Computing Platform." *ISPRS Journal of Photogrammetry and Remote Sensing* 131: 104–120. doi:[10.1016/j.isprsjprs.2017.07.011](https://doi.org/10.1016/j.isprsjprs.2017.07.011).
- Cui, X., J. Liang, W. Lu, H. Chen, F. Liu, G. Lin, F. Xu, Y. Luo, and G. Lin. 2018. "Stronger Ecosystem Carbon Sequestration Potential of Mangrove Wetlands with Respect to Terrestrial Forests in Subtropical China." *Agricultural and Forest Meteorology* 249: 71–80. doi:[10.1016/j.agrformet.2017.11.019](https://doi.org/10.1016/j.agrformet.2017.11.019).
- Feka, Z. N. 2015. "Sustainable Management of Mangrove Forests in West Africa: A New Policy Perspective?" *Ocean & Coastal Management* 116: 341–352. doi:[10.1016/j.ocecoaman.2015.08.006](https://doi.org/10.1016/j.ocecoaman.2015.08.006).
- Feller, I. C., C. E. Lovelock, U. Berger, K. L. McKee, S. B. Joye, and M. C. Ball. 2010. "Biocomplexity in Mangrove Ecosystems." *Annual Review of Marine Science* 2: 395–417. doi:[10.1146/annurev.marine.010908.163809](https://doi.org/10.1146/annurev.marine.010908.163809).
- Fent, A., R. Bardou, J. Carney, and K. Cavanaugh. 2019. "Transborder Political Ecology of Mangroves in Senegal and the Gambia." *Global Environmental Change* 54: 214–226. doi:[10.1016/j.gloenvcha.2019.01.003](https://doi.org/10.1016/j.gloenvcha.2019.01.003).
- Ferrier, S., and A. Guisan. 2006. "Spatial Modelling of Biodiversity at the Community Level." *The Journal of Applied Ecology* 43 (3): 393–404. doi:[10.1111/j.1365-2664.2006.01149.x](https://doi.org/10.1111/j.1365-2664.2006.01149.x).
- Ferwerda, J. G., S. D. Jones, and M. Reston. 2006. "A Free Online Reference Library for Hyperspectral Reflectance Signatures." *SPIE Newsroom* 1. doi:[10.1117/2.1200612.0551](https://doi.org/10.1117/2.1200612.0551).
- Field, C. D. 1999. "Rehabilitation of Mangrove Ecosystems: An Overview." *Marine pollution bulletin* 37 (8–12): 383–392. doi:[10.1016/S0025-326X\(99\)00106-X](https://doi.org/10.1016/S0025-326X(99)00106-X).
- Franklin, J. 1995. "Predictive Vegetation Mapping: Geographic Modelling of Biospatial Patterns in Relation to Environmental Gradients." *Progress in Physical Geography* 19 (4): 474–499. doi:[10.1177/030913339501900403](https://doi.org/10.1177/030913339501900403).
- Gilani, H., H. Iqra Naz, M. Arshad, K. Nazim, U. Akram, A. Abrar, and M. Asif. 2021. "Evaluating Mangrove Conservation and Sustainability Through Spatiotemporal (1990–2020) Mangrove Cover Change Analysis in Pakistan." *Estuarine, Coastal and Shelf Science* 249: 107128. doi:[10.1016/j.ecss.2020.107128](https://doi.org/10.1016/j.ecss.2020.107128).
- Giri, C., and J. Long. 2016. "Is the Geographic Range of Mangrove Forests in the Conterminous United States Really Expanding?" *Sensors* 16 (12): 2010. doi:[10.3390/s16122010](https://doi.org/10.3390/s16122010).
- Giri, C., E. Ochieng, L. L. Tieszen, Z. Zhu, A. Singh, T. Loveland, and N. Duke. 2011. "Status and Distribution of Mangrove Forests of the World Using Earth Observation Satellite Data." *Global Ecology and Biogeography* 20 (1): 154–159. doi:[10.1111/j.1466-8238.2010.00584.x](https://doi.org/10.1111/j.1466-8238.2010.00584.x).
- Giri, C., E. Ochieng, L. L. Tieszen, Z. Zhu, A. Singh, T. Loveland, J. Masek, and N. Duke. 2011. "Status and Distribution of Mangrove Forests of the World Using Earth Observation Satellite Data." *Global Ecology and Biogeography* 20 (1): 154–159. doi:[10.1111/j.1466-8238.2010.00584.x](https://doi.org/10.1111/j.1466-8238.2010.00584.x).

- Giri, C., Z. Zhu, L.L. Tieszen, A. Singh, S. Gillette, and J.A. Kelmelis. 2008. "Mangrove Forest Distributions and Dynamics (1975–2005) of the Tsunami-affected Region of Asia." *Journal of Biogeography* 35 (3): 519–528. doi:10.1111/j.1365-2699.2007.01806.x.
- Goldberg, L., D. Lagomasino, N. Thomas, and T. Fatoyinbo. 2020. "Global Declines in Human-driven Mangrove Loss." *Global Change Biology* 26 (10): 5844–5855. doi:10.1111/gcb.15275.
- Guo, Y., J. Liao, and G. Shen. 2021. "Mapping Large-Scale Mangroves Along the Maritime Silk Road from 1990 to 2015 Using a Novel Deep Learning Model and Landsat Data." *Remote Sensing* 13 (2): 245. doi:10.3390/rs13020245.
- Hamilton, S. E. 2016. "Introducing CGMFC-21 (Continuous Global Mangrove Forest Cover for the 21st Century)." *GLOMIS/ISME* 14 (3): 11–14.
- Hamilton, S. E., and D. Casey. 2016. "Creation of a High Spatio-temporal Resolution Global Database of Continuous Mangrove Forest Cover for the 21st Century (CGMFC-21)." *Global Ecology and Biogeography* 25 (6): 729–738. doi:10.1111/geb.12449.
- Heumann, B. W. 2011. "Satellite Remote Sensing of Mangrove Forests: Recent Advances and Future Opportunities." *Progress in Physical Geography* 35 (1): 87–108. doi:10.1177/0309133310385371.
- Hueni, A., J. Niek, J. Schopfer, M. Kneubühler, and K. I. Itten. 2009. "The Spectral Database SPECCHIO for Improved Long-Term Usability and Data Sharing." *Computers & Geosciences* 35 (3): 557–565. doi:10.1016/j.cageo.2008.03.015.
- Huylenbroeck, L., M. Laslier, S. Dufour, B. Georges, P. Lejeune, and A. Michez. 2020. "Using Remote Sensing to Characterize Riparian Vegetation: A Review of Available Tools and Perspectives for Managers." *Journal of environmental management* 267: 110652. doi:10.1016/j.jenvman.2020.110652.
- Jia, M., Z. Wang, Y. Zhang, D. Mao, and C. Wang. 2018. "Monitoring Loss and Recovery of Mangrove Forests During 42 Years: The Achievements of Mangrove Conservation in China." *International Journal of Applied Earth Observation and Geoinformation* 73: 535–545. doi:10.1016/j.jag.2018.07.025.
- Kirui, K.B., J.G. Kairo, J. Bosire, K.M. Viergever, S. Rudra, M. Huxham, and R.A. Briers. 2013. "Mapping of Mangrove Forest Land Cover Change Along the Kenya Coastline Using Landsat Imagery." *Ocean & Coastal Management* 83: 19–24. doi:10.1016/j.ocecoaman.2011.12.004.
- Kovacs, J.M., X.X. Lu, F. Flores-Verdugo, C. Zhang, F. Flores de Santiago, and X. Jiao. 2013. "Applications of ALOS PALSAR for Monitoring Biophysical Parameters of a Degraded Black Mangrove (*Avicennia Germinans*) Forest." *ISPRS Journal of Photogrammetry and Remote Sensing* 82: 102–111. doi:10.1016/j.isprsjprs.2013.05.004.
- Kuenzer, C., A. Bluemel, S. Gebhardt, T. Vo Quoc, and S. Dech. 2011. "Remote Sensing of Mangrove Ecosystems: A Review." *Remote Sensing* 3 (5): 878–928. doi:10.3390/rs3050878.
- Laffoley, D., and Grimsditch G. D. 2009. *The Management of Natural Coastal Carbon Sinks*. Switzerland: International Union for Conservation of Nature.
- Lymburner, L., P. Bunting, R. Lucas, P. Scarth, I. Alam, C. Phillips, C. Ticehurst, and A. Held. 2020. "Mapping the Multi-Decadal Mangrove Dynamics of the Australian Coastline." *Remote Sensing of Environment* 238: 111185. doi:10.1016/j.rse.2019.05.004.
- Mackey, B. G., and D. B. Lindenmayer. 2001. "Towards a Hierarchical Framework for Modelling the Spatial Distribution of Animals." *Journal of Biogeography* 28 (9): 1147–1166. doi:10.1046/j.1365-2699.2001.00626.x.
- Mazda, Y., N. Kanazawa, and E. Wolanski. 1995. "Tidal Asymmetry in Mangrove Creeks." *Hydrobiologia* 295 (1): 51–58. doi:10.1007/BF00029110.
- Moore, G. E., B. F. Gilmer, and S. R. Schill. 2015. "Distribution of Mangrove Habitats of Grenada and the Grenadines." *Journal of Coastal Research* 31 (1): 155–162. doi:10.2112/JCOASTRES-D-13-00187.1.
- Muchoney, D., J. Borak, H. Chi, M. Friedl, S. Gopal, J. Hodges, N. Morrow, and A. Strahler. 2000. "Application of the MODIS Global Supervised Classification Model to Vegetation and Land Cover Mapping of Central America." *International Journal of Remote Sensing* 21 (6–7): 1115–1138. doi:10.1080/014311600210100.
- Murray, M. R., S.A. Zisman, P. A. Furley, D. M. Munro, J. Gibson, J. Ratter, S. Bridgewater, C. D. Minty, and C. J. Place. 2003. "The Mangroves of Belize: Part 1. Distribution, Composition and Classification." *Forest Ecology and Management* 174 (1–3): 265–279. doi:10.1016/S0378-1127(02)00036-1.
- Nayak, S., and A. Bahuguna. 2001. "Application of Remote Sensing Data to Monitor Mangroves and Other Coastal Vegetation of India." *Indian Journal of Geo-Marine Sciences* 30(4): 195–213.

- Noor, T., N. Batool, R. Mazhar, and N. Ilyas. 2015. "Effects of Siltation, Temperature and Salinity on Mangrove Plants." *European Academic Research* 2 (11): 14172–14179.
- Pham, T. D., N. Yokoya, D. Tien Bui, K. Yoshino, and D. A. Friess. 2019. "Remote Sensing Approaches for Monitoring Mangrove Species, Structure, and Biomass: Opportunities and Challenges." *Remote Sensing* 11 (3): 230. doi:[10.3390/rs11030230](https://doi.org/10.3390/rs11030230).
- Primavera, J. H., and J. Morvenna a Esteban. 2008. "A Review of Mangrove Rehabilitation in the Philippines: Successes, Failures and Future Prospects." *Wetlands Ecology and Management* 16 (5): 345–358. doi:[10.1007/s11273-008-9101-y](https://doi.org/10.1007/s11273-008-9101-y).
- Razali, S. M., A. Ainuddin Nuruddin, and M. Lion. 2019. "Mangrove Vegetation Health Assessment Based on Remote Sensing Indices for Tanjung Piai, Malay Peninsular." *Journal of Landscape Ecology* 12 (2): 26–40. doi:[10.2478/jlecol-2019-0008](https://doi.org/10.2478/jlecol-2019-0008).
- Rivera-Monroy, V. H., S. Yip Lee, E. Kristensen, and R. R. Twilley. 2017. *Mangrove Ecosystems: A Global Biogeographic Perspective*. Germany: Springer.
- Ruiz-Jaén, M. C., and T. Mitchell Aide. 2005. "Vegetation Structure, Species Diversity, and Ecosystem Processes as Measures of Restoration Success." *Forest Ecology and Management* 218 (1–3): 159–173. doi:[10.1016/j.foreco.2005.07.008](https://doi.org/10.1016/j.foreco.2005.07.008).
- Sakti, A. D., A. Irwansyah Fauzi, F. Niwan Wilwatikta, Y. Sepwanto Rajagukguk, S. Adhitya Sudhana, L. Fajri Yayusman, L. Nurlaila Syahid, T. Sritarapipat, J. A. Principe, and N. Thi Quynh Trang. 2020. "Multi-Source Remote Sensing Data Product Analysis: Investigating Anthropogenic and Naturogenic Impacts on Mangroves in Southeast Asia." *Remote Sensing* 12 (17): 2720. doi:[10.3390/rs12172720](https://doi.org/10.3390/rs12172720).
- Sanderman, J., T. Hengli, G. Fiske, K. Solvik, M. Fernanda Adame, L. Benson, J. J. Bukoski, P. Carnell, M. Cifuentes-Jara, and D. Donato. 2018. "A Global Map of Mangrove Forest Soil Carbon at 30 M Spatial Resolution." *Environmental Research Letters* 13 (5): 055002. doi:[10.1088/1748-9326/aabe1c](https://doi.org/10.1088/1748-9326/aabe1c).
- Sasmitho, S. D., P. Taillardat, J. N. Clendenning, C. Cameron, D. A. Friess, D. Murdiyarso, and L. B. Hutley. 2019. "Effect of Land-use and Land-cover Change on Mangrove Blue Carbon: A Systematic Review." *Global Change Biology* 25 (12): 4291–4302. doi:[10.1111/gcb.14774](https://doi.org/10.1111/gcb.14774).
- Shang, R., R. Liu, M. Xu, Y. Liu, L. Zuo, and Q. Ge. 2017. "The Relationship Between Threshold-Based and Inflexion-Based Approaches for Extraction of Land Surface Phenology." *Remote Sensing of Environment* 199: 167–170. doi:[10.1016/j.rse.2017.07.020](https://doi.org/10.1016/j.rse.2017.07.020).
- Simard, M., L. Fatoyinbo, C. Smetanka, V. H. Rivera-Monroy, E. Castañeda-Moya, N. Thomas, and T. Van der Stocken. 2019. "Mangrove Canopy Height Globally Related to Precipitation, Temperature and Cyclone Frequency." *Nature geoscience* 12 (1): 40–45. doi:[10.1038/s41561-018-0279-1](https://doi.org/10.1038/s41561-018-0279-1).
- Spalding, M.D., Leal, M. 2021. *The State of the World's Mangroves 2021* Global Mangrove Alliance.
- Syahid, L. N., A. Dimara Sakti, R. Virtriana, K. Wikantika, W. Windupranata, S. Tsuyuki, R. Eko Caraka, and R. Pribadi. 2020. "Determining Optimal Location for Mangrove Planting Using Remote Sensing and Climate Model Projection in Southeast Asia." *Remote Sensing* 12 (22): 3734. doi:[10.3390/rs12223734](https://doi.org/10.3390/rs12223734).
- Taillie, P. J., R. Roman-Cuesta, D. Lagomasino, M. Cifuentes-Jara, T. Fatoyinbo, L. E. Ott, and B. Poulter. 2020. "Widespread Mangrove Damage Resulting from the 2017 Atlantic Mega Hurricane Season." *Environmental Research Letters* 15 (6): 064010. doi:[10.1088/1748-9326/ab82cf](https://doi.org/10.1088/1748-9326/ab82cf).
- Temudo, M. P., and A. Isabel Cabral. 2017. "The Social Dynamics of Mangrove Forests in Guinea-Bissau, West Africa." *Human Ecology* 45 (3): 307–320. doi:[10.1007/s10745-017-9907-4](https://doi.org/10.1007/s10745-017-9907-4).
- Thomas, N., R. Lucas, P. Bunting, A. Hardy, A. Rosenqvist, and M. Simard. 2017. "Distribution and Drivers of Global Mangrove Forest Change, 1996–2010." *PloS One* 12 (6): e0179302. doi:[10.1371/journal.pone.0179302](https://doi.org/10.1371/journal.pone.0179302).
- Valle, D., M. E. Alejandro, O. A. Ishizawa, and J. Jose Miranda. 2020. "Mangroves Protect Coastal Economic Activity from Hurricanes." *Proceedings of the National Academy of Sciences* 117 (1): 265–270. doi:[10.1073/pnas.1911617116](https://doi.org/10.1073/pnas.1911617116).
- Walters, B. B., P. Rönnbäck, J. M. Kovacs, B. Crona, S. Ainul Hussain, R. Badola, J. H. Primavera, E. Barbier, and F. Dahdouh-Guebas. 2008. "Ethnobiology, Socio-Economics and Management of Mangrove Forests: A Review." *Aquatic Botany* 89 (2): 220–236.
- Walter, J. A., A. E. Stovall, and J. W. Atkins. 2021. "Vegetation Structural Complexity and Biodiversity in the Great Smoky Mountains." *Ecosphere* 12 (3): e03390.

- Wang, L., M. Jia, D. Yin, and J. Tian. 2019. "A Review of Remote Sensing for Mangrove Forests: 1956–2018." *Remote Sensing of Environment* 231: 111223. doi:[10.1016/j.rse.2019.111223](https://doi.org/10.1016/j.rse.2019.111223).
- Wang, J., T. W. Sammis, V. P. Gutschick, M. Gebremichael, S. O. Dennis, and R. E. Harrison. 2010. "Review of Satellite Remote Sensing Use in Forest Health Studies." *The Open Geography Journal* 3 (1): 28–42. doi:[10.2174/1874923201003010028](https://doi.org/10.2174/1874923201003010028).
- Wang, L., C. Shi, J. Tian, X. Song, M. Jia, X. Li, X. Liu, et al. 2018. "Researches on Mangrove Forest Monitoring Methods Based on Multi-Source Remote Sensing." *Biodiversity Science* 26 (8): 838. doi:[10.17520/biods.2018067](https://doi.org/10.17520/biods.2018067).
- Wang, L., W. P. Sousa, P. Gong, and G. S. Biging. 2004. "Comparison of IKONOS and QuickBird Images for Mapping Mangrove Species on the Caribbean Coast of Panama." *Remote Sensing of Environment* 91 (3–4): 432–440. doi:[10.1016/j.rse.2004.04.005](https://doi.org/10.1016/j.rse.2004.04.005).
- Wang, D., B. Wan, P. Qiu, Y. Su, Q. Guo, and X. Wu. 2018. "Artificial Mangrove Species Mapping Using Pleiades-1: An Evaluation of Pixel-Based and Object-Based Classifications with Selected Machine Learning Algorithms." *Remote Sensing* 10 (2): 294. doi:[10.3390/rs10020294](https://doi.org/10.3390/rs10020294).
- Wilcove, D. S. 1986 "Habitat Fragmentation in the Temperate Zone Soule, M. E." In *Conservation Biology: The Science of Scarcity and Diversity* Sinauer Associates: the United States.237–256.
- Wilwatikta, F.N., A.D. Sakti, L.N. Syahid, and K. Wikantika. 2020. "The Influence of Water Balance in Mangrove Forests Growth to Mangrove's Degradation and Depletion, Case Study: Southeast Asia." *IOP Conference Series: Earth and Environmental Science* 500: 012013 doi:[10.1088/1755-1315/500/1/012013](https://doi.org/10.1088/1755-1315/500/1/012013).
- Worthington, T. A., D. A. Andradi-Brown, R. Bhargava, C. Buelow, P. Bunting, C. Duncan, L. Fatoyinbo, D. A. Friess, L. Goldberg, and L. Hilarides. 2020. "Harnessing Big Data to Support the Conservation and Rehabilitation of Mangrove Forests Globally." *One Earth* 2 (5): 429–443. doi:[10.1016/j.oneear.2020.04.018](https://doi.org/10.1016/j.oneear.2020.04.018).
- Ximenes, A. C., E. Eiji Maeda, G. Felipe Balué Arcoverde, and F. Dahdouh-Guebas. 2016. "Spatial Assessment of the Bioclimatic and Environmental Factors Driving Mangrove Tree Species' Distribution Along the Brazilian Coastline." *Remote Sensing* 8 (6): 451. doi:[10.3390/rs8060451](https://doi.org/10.3390/rs8060451).
- Yee, S. 2010. "REDD and BLUE Carbon: Carbon Payments for Mangrove Conservation." Center for Marine Biodiversity and Conservation.
- Ying, L., and L. Wang. 2021. "How to Automate Timely Large-Scale Mangrove Mapping with Remote Sensing." *Remote Sensing of Environment* 264: 112584. doi:[10.1016/j.rse.2021.112584](https://doi.org/10.1016/j.rse.2021.112584).
- Zanvo, M. S., Y.S. Sabas Barima, K. Valère Salako, K.A. Noël Koua, M. A. Kolawole, A. Ephrem Assogbadjo, and R. Glèlè Kakai. 2021. "Mapping Spatio-Temporal Changes in Mangroves Cover and Projection in 2050 of Their Future State in Benin." *BOIS & FORETS DES TROPIQUES* 350: 29–42. doi:[10.19182/bft2021.350.a36828](https://doi.org/10.19182/bft2021.350.a36828).
- Zhang, Z., X. Dong, J. Tian, Q. Tian, Y. Xi, and D. He. 2022. "Stand Density Estimation Based on Fractional Vegetation Coverage from Sentinel-2 Satellite Imagery." *International Journal of Applied Earth Observation and Geoinformation* 108: 102760. doi:[10.1016/j.jag.2022.102760](https://doi.org/10.1016/j.jag.2022.102760).
- Zhang, J., X. Yang, Z. Wang, T. Zhang, and X. Liu. 2021. "Remote Sensing Based Spatial-Temporal Monitoring of the Changes in Coastline Mangrove Forests in China Over the Last 40 Years." *Remote Sensing* 13 (10): 1986. doi:[10.3390/rs13101986](https://doi.org/10.3390/rs13101986).
- Zheng, Y., Z. Niu, P. Gong, and J. Wang. 2015. "A Database of Global Wetland Validation Samples for Wetland Mapping." *Science Bulletin* 60 (4): 428–434. doi:[10.1007/s11434-014-0717-4](https://doi.org/10.1007/s11434-014-0717-4).