



Article

Distinguishing Original and Non-Original Stands at the Zhanjiang Mangrove National Nature Reserve (P.R. China): Remote Sensing and GIS for Conservation and Ecological Research

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Abstract: The present research developed a novel methodological framework to differentiate natural mangrove stands (i.e., original), from stands which were planted and stands naturally established after interaction between planted and non-planted stands (e.g., through pollination, i.e., non-original). Ground-truth and remote sensing data were collected for Zhanjiang Mangrove National Nature Reserve (ZMNRR) in P.R. China. First, satellite images of Corona (1967) and GeoEye-1 (2009) were overlaid to identify original (1967) and non-original (2009) mangrove stands. Second, in both stands a total of 75 in situ plots (25 m²) were measured for ground-truthing of tree structural parameters including height, density, basal area and Complexity Index (CI). From temporal satellite data, we identify 236.12 ha of original mangrove and 567.88 ha of non-original mangrove in the reserve. Averaged measurements of the original mangrove stands, i.e., stem density (1164 nos. 0.1 ha⁻¹), basal area (90.3 m² 0.1 ha⁻¹) and CI (100.59), indicated that they were in a state of maturity and less disturbed compared to the non-original mangroves (density, 1241 nos. 0.1 ha⁻¹; basal area, 4.92 m² 0.1 ha⁻¹ and CI, 55.65). The Kruskal–Wallis test showed significant differentiation between the original and non-original mangrove tree structural parameters: *Kandelia obovata*'s density, $X^2 = 34.78$, d.f. = 1, $p = 0.001$; basal area, $X^2 = 108.15$, d.f. = 1, $p = 0.001$; *Rizhopora stylosa*'s density, $X^2 = 64.03$, d.f. = 1, $p = 0.001$; basal area, $X^2 = 117.96$, d.f. = 1, $p = 0.001$. The latter is also evident from the clustering plots generated from the Principal Component Analysis (PCA). Vegetation dynamics at the ZMNRR also enabled us to compare the species composition and distribution patterns with other Indo-West Pacific regions. Overall, the present study not only highlights the advantage of >50 years old satellite data but also provide a benchmark for future ecological research, conservation and management of the ZMNRR.

Keywords: spatial distribution; vegetation structure; original forest; remote sensing; GIS

1. Introduction

The significance and conservation of mangrove forests rely on their economic, social and ecological service values [1–3]. Mangroves are among the most carbon-rich forests in the tropics [4–6] and can function as phytoremediators [7–9]. In fact, such mangrove benefits are often highlighted by scientists as well as government and non-governmental agencies [10–12]. Although the rate of global mangrove cover loss has been decreasing in recent years [13], efficient mangrove management through improved/sustainable practices still remains as a concern for many countries [12,14,15]. As mangrove areas are smaller or fragmented at several locations, the long-term survival of these forests is at risk and their essential ecosystem services might be lost [16–18]. For instance, 45% of carbon accumulated during the last century is lost due to mangrove clearing and soil exposure over 10 years which is equivalent to about 20% of the upper meter soil carbon stock [19]. The success of restoration efforts focuses upon its genetic diversity conservation (assessment before, during and after) in the face of multiple disturbance and habitat destruction scenarios, e.g., climate change and sea-level rise, aquaculture, pollution, etc. [20–22]. The term “original forest” has been previously used for describing mangroves that pre-date human intervention [23]. Original mangrove forests may have greater ecosystem service benefits than disturbed mangroves, e.g., a better carbon sink [24]. While it is a challenge to accurately map the original mangroves due to scarce available data [25], promising new initiatives are in development [26]. It is estimated that 35–84% (depending on the locality) of the original mangrove has been lost to anthropogenic activities [27] and regional and global trends are worrying [28,29]. Therefore, conservation of the remaining original mangrove forests needs our utmost attention [30,31].

In addition to the natural and anthropogenic impacts on mangrove covers, inbreeding might reduce reproductive potentials (along with loss of genetic diversity) and its resilience towards environmental change [32,33]. Since long-term survival of a species depends on its genetic conservation, molecular marker methods have been used to evaluate genetic characteristics, such as structure, flows, barriers, past sea-level changes [34–37]. However, these gene-tests are still limited due to lack of reliable historical data (e.g., forest age) from many mangrove locations. This is just one example for which the distinction between original and non-original stands proved to be helpful, but throughout ecology *sensu lato* multiple studies can be identified [38–53] (Table 1).

Continued monitoring and thorough assessments are the prerequisites to understand mangrove vegetation dynamics [54,55]. This can be achieved through various methods comprised of field-based investigations and remote sensing data [56,57]. Field-based monitoring is useful for mangrove studies, but remote sensing data with repeated temporal resolution is indispensable nowadays [55,58]. The use of Corona images enables us to study past dynamics before 1960 s, e.g., forest cover change [49] periglacial geomorphology in forests [59], deforestation [60]; but in the Web of Science[®] only 32 records of its use are indexed and in mangrove forest remains very rare [61,62]. In the case of Zhanjiang Mangrove National Nature Reserve (ZMNNR) in China, local authorities have carried out several mangrove plantations schemes during 1990s, but without holding a record on its geographical (i.e., latitude and longitude) coordinates. Hence, after two decades of forest development there is a great uncertainty about the original mangrove stands (here defined as community of trees naturally present before planting schemes) and the non-original ones (here defined as planted stands or stands that have naturally established after interaction between planted and original stands, for instance through pollination and reproduction).

The present study was primarily aimed at setting up a methodological framework to distinguish original and non-original mangrove stands at the ZMNNR for subsequent ecological research (conservation genetics, silviculture, etc.). The objectives were to find older and newer mangrove canopy patches using remote sensing data (i.e., Corona of 1967 and GeoEye-1 of 2009), and to estimate as well as compare the stand structural attributes (density, basal area, height) between these two patches. Recommendations on suitable

sites for a wide range of mangrove ecological researches along with its conservation and management at the ZMNNR were formulated.

Table 1. Ecological studies for which the distinction between original and non-original stands may be required. The example references are indicative of the relevance of the field, but did not distinguish between original and non-original stands.

Hypothetical Ecological Study Objectives	Field	Example Reference(s)
to execute sampling for conservation genetics	Conservation genetics	Binks et al., 2019; Ragavan et al., 2017
to estimate tree age	Silviculture	Lucas et al., 2020
to identify late successional stands (e.g., capable of mass seeding)	Reproductive botany	Dangremond and Feller, 2016
to outline core conservation areas to monitor gain/loss of pristine forest	Environmental planning	Borges et al., 2017; Song et al., 2015
to sample species indicative of floristic or faunistic recruitment	Restoration ecology	Bosire et al., 2008; Salmo et al., 2013
to monitor soil biogeochemical processes in interior stands	Biogeochemistry	Lee et al., 2008
to compare microbial activity in outer and interior stands	Environmental microbiology	Pupin and Nahas, 2014
to detect/validate older mangrove presence using spectral analysis in up-to-date high-resolution images	Earth observation science	Andersen, 2006; Otero et al., 2019; Song et al., 2015
to monitor hydrological process in interior stands	Forest hydrology	Luo and Chui, 2020
to test forest resilience in interior stands after disturbance	Forestry science	Nikinmaa et al., 2020
to compare sediment and geological formations in interior stands	Sedimentology	Swales et al., 2019; Swales and Lovelock, 2020

2. Materials and Methods

2.1. Study Area

The Guangdong province in China hosts nearly 50% of the country's mangrove cover of which 12,375 ha (80%) is found in Leizhou Peninsula [63]. The ZMNNR is located along the coastline facing South China Sea's Ying Luo Bay (Figure 1). The mangrove vegetation is composed of five dominant species namely, *Aegiceras corniculatum* (L.) Blanco, *Avicennia marina* (Forsk.) Vierh., *Bruguiera gymnorrhiza* (L.) Lamk., *Kandelia obovata* (L.) Druce, *Rhizophora stylosa* Griff., and two non-dominant species namely, *Sonneratia apetala* Buch. –Ham, and *Excoecaria agallocha* (L.) [63]. Besides the loss of mangrove forests to coastal erosion, both rice cultivation and aquaculture were the major anthropogenic threats to the ZMNNR [62]. Yet, the ZMNNR has acquired the status of Ramsar Wetland of International Importance (no. 1157) in 2002 for its ecological significance as a waterfowl habitat [64]. The local authorities have carried out several mangrove plantations in the vicinity during 1990s, especially *S. apetala* (a non-native and invasive species). We were informed by ZMMNR officials that it was a planted species thus we excluded studied plots within these areas in the present study. *E. agallocha* was also planted, but it had very few individuals [62]. The study area is characterized by northern tropical climate with a mean annual temperature of 25 °C (min = 15 °C, max = 32 °C) and precipitation of 1480 mm [65]. The tides are diurnal in nature with an average salinity of 4.17 ± 1.17 ppt and pH 5.14 ± 0.41 [66].

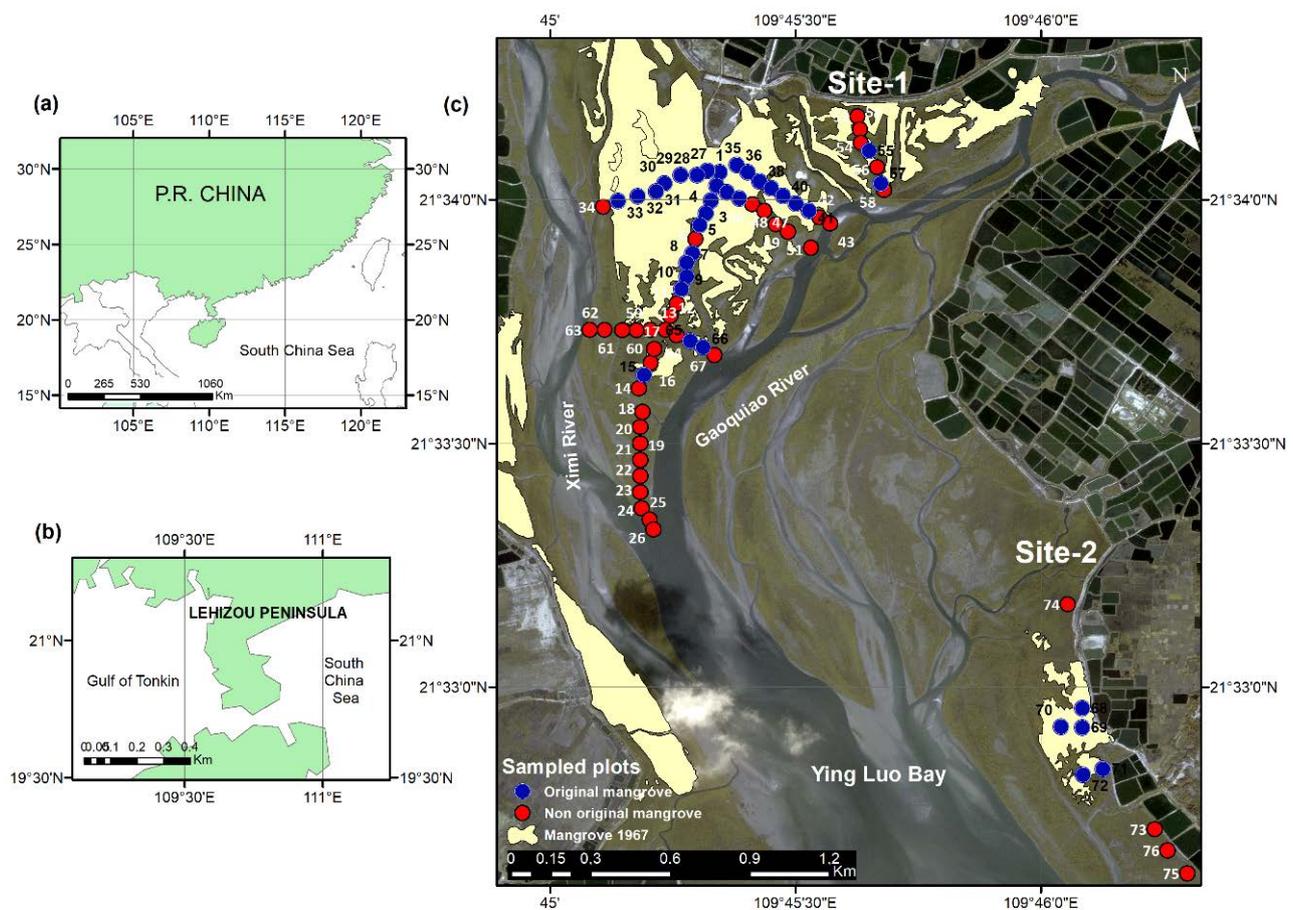


Figure 1. (a,b) The location of Zhanjiang Mangrove National Nature Reserve (ZMNRR) in southern China, under the jurisdiction of Leihizou Peninsula in Guangdong Province; (c) the extent of ZMNRR mangrove cover observed on GeoEye-1 satellite image dated 16 October 2009. The mangrove extent of 1967 (cream-colored polygons) was observed from Corona KH-4B satellite imagery dated 17 December 1967. Sites (1) and (2) were the areas investigated for present study. Sampling points (blue dots) in the original mangrove stands: 1–5, 7–10, 12, 13, 28–33, 35–38, 45, 46, 48, 58, 59, 64, 67–72 plot numbers. Sampling points (red dots) in the non-original mangrove stands: 6, 11, 14–18, 19, 20–26, 27, 34, 39–44, 47, 49–57, 60–63, 65, 66, 73–76 plot numbers.

2.2. Forest Stands Identification Methodological Framework

The summarized steps of methodology were shown in Figure 2, while complete details are provided in the Sections 2.3–2.5 below.

2.3. Remote Sensing Data

For mangrove spatio-temporal change detection, the Corona KH-4B panchromatic satellite imagery dated 17 December 1967 (declassified US military programs) (spatial resolution: 1.8 m) and GeoEye-1 multispectral satellite imagery dated 16 October 2009 (spatial resolution: 1.65 m for the multispectral bands and 0.5 m for the panchromatic band) were used. At first the mangrove extent in both images was thoroughly checked through visual interpretation in raw imagery (Figure A1) as well as in several false color composites. The combination of red = 4; green = 3; blue = 2 enabled us to visually identify presumed original and non-original forest (Figure A2). The black areas in the Corona imagery were decisive in guided us through the process. Second, the Corona image was georeferenced (ground control points = 34; total root mean square error = 11.59; transformation = 1st order polynomial) using features initially identified from the GeoEye-1 (after pan-sharpening with the Gram–Schmidt algorithm [67], which implemented band weights in the enhancement procedure for red = 0.6, green = 0.85, blue = 0.75, and infrared = 0.3 [68]), and the mangrove

stands in both images were digitized (ArcMap 10.5). Third, the digitized polygons were overlaid to identify original/non-original mangrove stands and to calculate the area statistics. The polygons of 1967 that overlapped with visible putative older-grown mangrove cover on 2009 imagery represents original mangrove. Non-intersected areas (between 1967 and 2009 images) with extended putative novel and young-growing mangrove cover from 1967 imagery represents non-original mangrove stand at the ZMNNR (Figures 1c and A1).

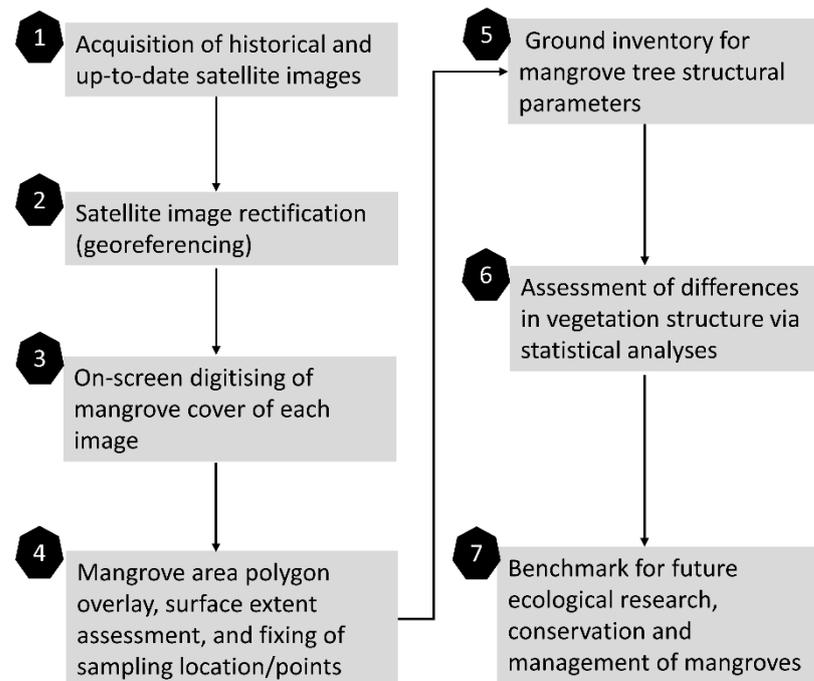


Figure 2. Methodological approach for identifying original and non-original mangrove stands at the Zhanjiang Mangrove National Nature Reserve (ZMNNR), China.

2.4. Ground-Truth Data

Ground inventory was carried out from Sites 1 and 2 covering original and non-original mangrove stands in August–September 2009 and April–May 2011 (Figure 1c). These two sites were chosen based on the conspicuous vegetation patches (thick black tone areas) that indicate mangrove in 1967. Altogether, 76 sampling points were chosen. Altogether, 76 sampling points were chosen using the belt transect method [69], of which 65 points are located in Site 1 and 9 in Site 2. Among those 65 points at Site 1, 37 represent the original mangrove and 29 non-original mangroves. At Site 2, five sampling points represented the original and four the non-original mangrove stands. At each sample point, a 5×5 m plot was established to record the species available by following the detailed taxonomic descriptions of Tomlinson [70], height (using a Sunnto clinometer PM-5/360, Finland), no. of stems and its diameter (D_{130}) [71], except for smaller species ($D_{h/2}$, where h = the height of the tree), after which we estimated different vegetation parameters including density (nos. ha^{-1}), basal area ($\text{m}^2 \text{ha}^{-1}$), relative density (%), relative dominance (%), relative frequency (%), Importance Value (IV), and Holdridge et al. (Complexity Index (CI) (1971) following the standard protocols [72–74].

IV and CI are defined as:

$$I.V. = De_r + Do_r + F_r \quad (1)$$

$$C.I. = \frac{De \times Ba \times H \times N}{1000} \quad (2)$$

where De_r is the relative density, Do_r the relative dominance, F_r the relative frequency, De the absolute density, Ba the (absolute) basal area, H the mean height, and N the number of species. These vegetation metrics were calculated using Excel[®] software (V16.0).

2.5. Mangrove Community Structural Analysis

Tree density and basal area have been suggested to differentiate young from late successional and grown-up forest [55]. We have investigated whether the sampled means of tree density, basal area and height can be used to separate original and non-original mangrove stands, through statistical analysis in R software [75]. Statistical variation among the vegetation parameters was checked through Kruskal–Wallis test (H) with post hoc Wilcoxon rank-sum test (T) or Analysis of Variance (ANOVA) with Student's *t*-test as per its applicability (root-transformed data to reduce heteroscedasticity). Significance levels ($p < \alpha$) for successive pair-wise multiple comparison of sampled plots were adjusted using Bonferroni correction [76]. Principal Component Analyses (PCA) with an ordihull function was run to indicate the original mangrove stands (i.e., sampled plots) for future ecological research, conservation and management purposes. An ordihull function is normally used to display groups or factor levels in ordination diagrams [75]. All mapping treatments from Sections 2.3 and 2.4 were performed in ArcMap v.10.5.

3. Results

3.1. Mangrove Vegetation Structure and Distinction of Original and Non-Original Stands

Satellite data indicated that the mangrove extent in ZMNRR increased from 236.12 ha in 1967 to 567.88 ha in 2009. Among others, *Aegiceras corniculatum* was found to be an important species with a wide range of distribution in both original and non-original stands whereas *Avicennia marina* is confined to non-original stands (Table 2). Complexity index was higher in the original stands (100.59) as opposed to the non-original ones (55.65) in Site 1, and lower in original stands (5.59) as opposed to the non-original ones (9.73) in Site 2 (Table 2). The tree structural parameters were represented by significant differences among species (Table 3) except for height of *A. corniculatum* and *Bruguiera gymnorhiza*.

The PCA showed two distinct clusters of sampling points for original and non-original, with some overlapping in the intersection, in relation to (mean) tree height measurements (cumulative variation: 63%) (Table 3, Figure 3). Whereas the cluster in blue represents the points exclusive to original mangrove (height, 3.25 m), the red shows non-original mangrove (height, 1.79 m) (Figure 3). The intersection area of these two clusters contained the sampling points of both original and non-original mangrove stands (height, 2.29 m).

The total stem density and basal area measurements also show similar trend of separation between original and non-original sampling points (Figures 4 and 5). All plots were categorized according to the PCA to original, non-original and those at the intersection. Positive eigenvalues on axes 1 and 2 were associated with *A. marina* (Table 4), species only encountered in non-original stands (Table 1). Negative eigenvalues were associated with *B. gymnorhiza* and *Kandelia ovobata*, which had higher values for all parameters for original stands and these species present also within non-original stands in Site 1 (Table 2). Every single plot identified within the PCA ordinations (Figures 3–5) was classified as original or non-original. Then, the ordihull function distinctly delineated original and non-original plots as well as an intersecting area comprising both original and non-original plots (Figures 3–5). The overlapping of all three structural parameters is highlighted in bold (Table A1). The intersection for stem density (Figure 4), *A. corniculatum* and *Rhizophora stylosa* are not separable as they presented positive and negative eigenvalues representing indistinct clustering (Table 3), but the overlapping cluster shows higher density values in original stands compared to non-original stands.

Table 2. Mangrove vegetation structural parameters representing original and non-original stands at Sites 1 and 2 (mean and min–max values in parentheses). Importance values (actual index value in parentheses) were denoted by rank numbers.

Species	Site 1		Site 2	
	Original	Non-Original	Original	Non-Original
Density (stems ha⁻¹)				
<i>Aegiceras corniculatum</i>	6480 (400–2800)	7093.3 (3200–19,600)	–	3750 (2000–5500)
<i>Avicennia marina</i>	–	1800 (400–5200)	–	1320 (320–2280)
<i>Bruguiera gymnorrhiza</i>	3186.7 (400–9200)	2114.3 (400–5600)	290 (80–720)	–
<i>Kandelia obovata</i>	1580 (400–6800)	711.1 (400–1200)	–	–
<i>Rhizophora stylosa</i>	400 (340–460)	700 (390–1200)	5360 (340–640)	–
Height (m)				
<i>Aegiceras corniculatum</i>	2.27 (0.96–3.23)	1.63 (0.61–3.08)	–	2.00 (1.80–2.30)
<i>Avicennia marina</i>	–	1.08 (0.30–1.57)	–	1.93 (1.80–2.10)
<i>Bruguiera gymnorrhiza</i>	2.69 (1.57–3.85)	2.03 (0.98–3.04)	3.87 (2.50–4.68)	–
<i>Kandelia obovata</i>	2.74 (1.50–4.14)	2.16 (1.38–3.10)	–	–
<i>Rhizophora stylosa</i>	1.87 (1.87–1.87)	2.21 (1.70–2.88)	3.82 (2.50–4.60)	–
Basal area (m² ha⁻¹)				
<i>Aegiceras corniculatum</i>	10.8 (1.4–42.3)	17.9 (3.6–38.6)	–	8.8 (6.3–10.8)
<i>Avicennia marina</i>	–	5.6 (1.0–12.6)	–	4.6 (3.2–5.9)
<i>Bruguiera gymnorrhiza</i>	11.2 (2.0–23.6)	7.6 (1.7–16.5)	10.0 (4.7–13.6)	–
<i>Kandelia obovata</i>	6.4 (1.0–19.1)	5.5 (1.7–8.2)	–	–
<i>Rhizophora stylosa</i>	5.1 (3.3–9.3)	4.2 (1.4–9.9)	9.5 (6.4–1.2)	–
IV (rank numbers)				
<i>Aegiceras corniculatum</i>	2 (76.56)	1 (224.79)	–	1 (146.51)
<i>Avicennia marina</i>	–	4 (10.08)	–	2 (53.49)
<i>Bruguiera gymnorrhiza</i>	1 (170.78)	2 (41.90)	2 (67.07)	–
<i>Kandelia obovata</i>	3 (46.39)	3 (13.48)	–	–
<i>Rhizophora stylosa</i>	4 (5.14)	5 (7.89)	1 (232.93)	–
CI	100.59	55.65	5.59	9.73

Table 3. Statistical metrics among species in original and non-original stands in relation to different tree structural parameters at the Zhanjiang Mangrove National Nature Reserve (ZMNNR), China. F and t indicate those metrics follow normality: thus, Welch ANOVA and Student *t*-test were applied instead *H* and *T* tests.

Height	Kruskal–Wallis Test (<i>H</i>)		Wilcoxon Sum Rank Test with Bonferroni Correction (<i>T</i>)	
	χ^2	<i>p</i> -Value	Weight	<i>p</i> -Value
<i>Aegiceras corniculatum</i>	2.3164	0.08	835.5	0.1294
<i>Avicennia marina</i>	103.27	0.001 *	504	0.001 *
<i>Bruguiera gymnorrhiza</i>	2.5732	0.1087	1192	0.001 *
<i>Kandelia obovata</i>	10.811	0.001 *	915.5	0.001 *
<i>Rhizophora stylosa</i>	70.927	0.001*	697	0.9516
Density				
<i>Aegiceras corniculatum</i>	61.603	0.001 *	238	0.001 *
<i>Avicennia marina</i>	82.045	0.001 *	504	0.001 *
<i>Bruguiera gymnorrhiza</i>	f = 45.6	0.001 *	t = −7.017	0.001 *
<i>Kandelia obovata</i>	34.780	0.001 *	874.5	0.02
<i>Rhizophora stylosa</i>	64.031	0.001 *	793	0.1285
Basal area				
<i>Aegiceras corniculatum</i>	f = 45.6	0.001 *	t = −6.050	0.001 *
<i>Avicennia marina</i>	123.71	0.001 *	504	0.001 *
<i>Bruguiera gymnorrhiza</i>	26.005	0.001 *	1159.5	0.001 *
<i>Kandelia obovata</i>	108.15	0.001 *	875.5	0.0267
<i>Rhizophora stylosa</i>	117.96	0.001 *	804.5	0.0898

* Confidence level at the 95%. Original and non-original mangrove separation (df = 1), species pairwise comparison (df = 72.75).

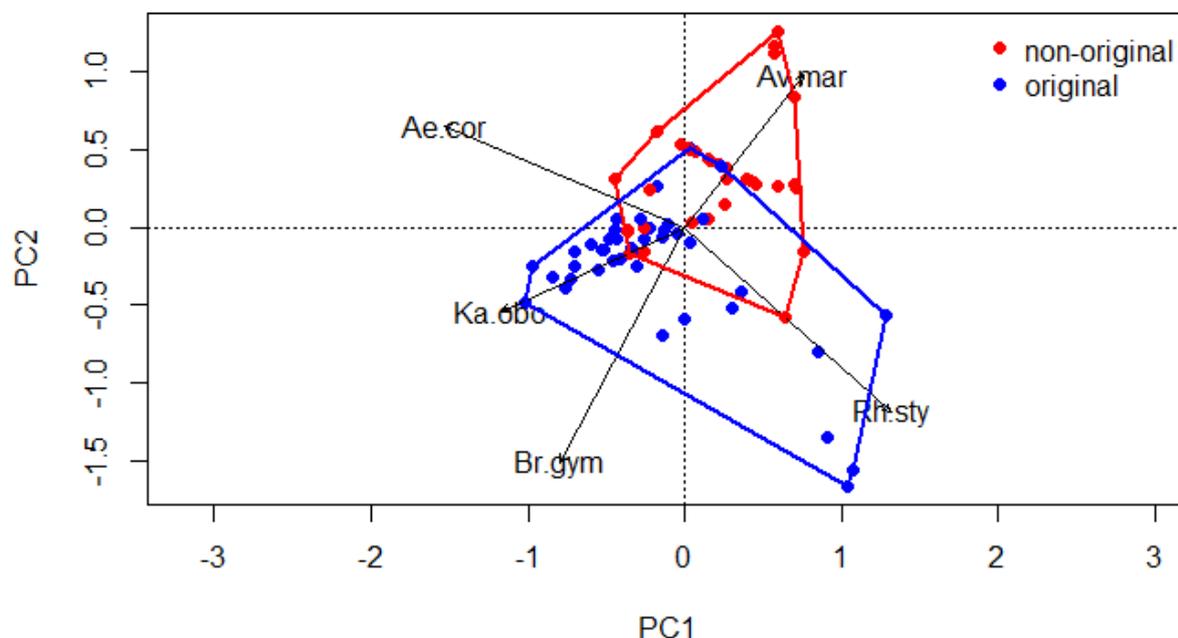


Figure 3. Principal component analysis showing the separability of sampling points in relation to tree height measurements of different species at original and non-original mangrove stands in the Zhanjiang Mangrove National Nature Reserve (ZMNNR), China. PC1 higher and negative eigenvalues showed taller trees, comprised by original trees, while PC1 high and positive eigenvalues showed *A. marina* and *R. stylosa*. PC2 higher and positive eigenvalues with *A. corniculatum*, *A. marina* for the non-original trees and PC2 higher and negative eigenvalues showed original trees (For better readability, sampling points to read from Table A1). Ae.cor = *Aegiceras corniculatum*, Br.gym = *Bruguiera gymnorrhiza*, Ka.obo = *Kandelia obovata*, Rh.sty = *Rhizophora stylosa*, Av.mar = *Avicennia marina*.

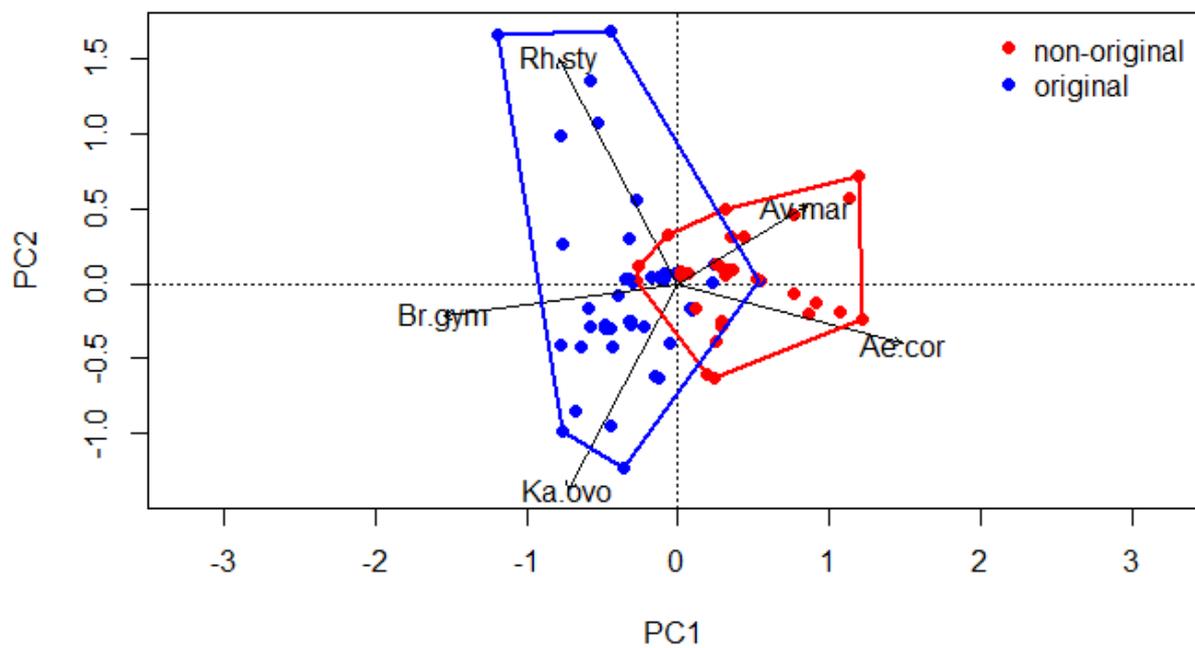


Figure 4. Principal component analysis showing the separability of sampling points in relation to stem density of different species at original and non-original mangrove stands in the Zhanjiang Mangrove National Nature Reserve (ZMNNR), China. PC1 higher negative eigenvalues pointed out species with lower densities represented by original trees while PC1 positive higher eigenvalues pointed out species with higher densities represented by non-original trees. PC2 higher positive eigenvalues showed an unclear pattern while PC2 higher negative eigenvalues showed original trees (for better readability, the sampling points to read are in Table A1). Species abbreviations to follow Figure 2.

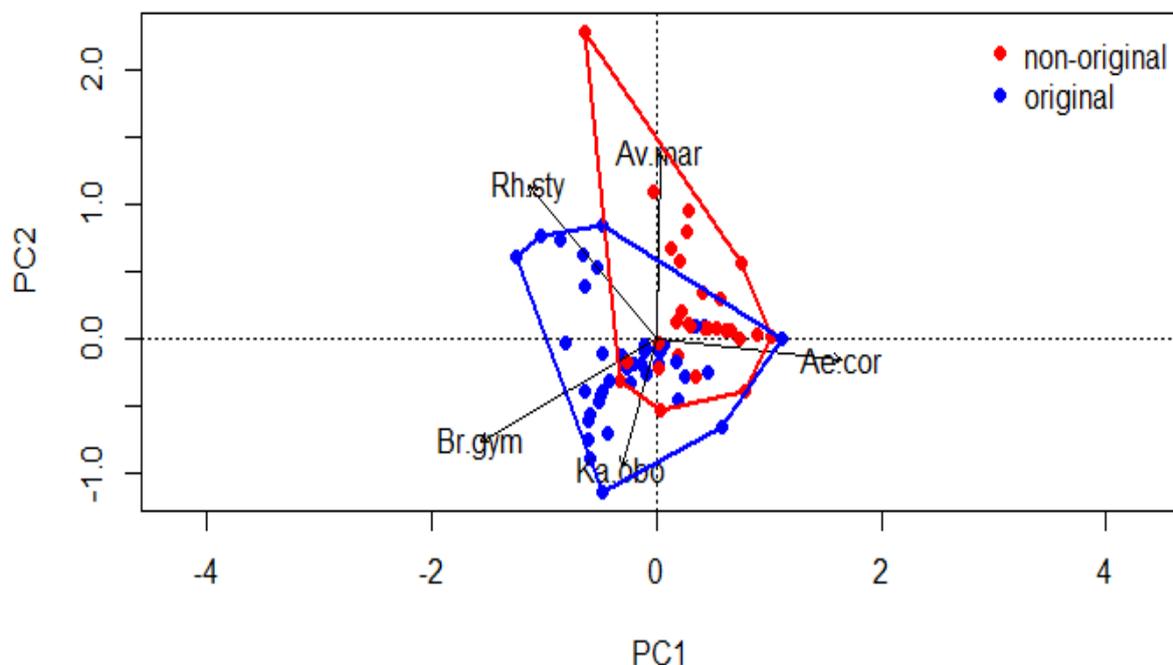


Figure 5. Principal component analysis showing the separability of sampling points in relation to basal area of different species at original and non-original mangrove stands in the Zhanjiang Mangrove National Nature Reserve (ZMNNR), China. PC1 higher negative eigenvalues showed original trees (higher basal area), PC1 positive eigenvectors correspond to *A. corniculatum* (lower basal area). PC2 higher positive eigenvectors showed *A. marina* and *R. stylosa*, both which are highly present as non-original mangrove (For better readability, sampling points to read from Table A1). Species abbreviations to follow Figure 2.

Table 4. Species eigenvalues and their cumulative proportion determined via Principal Component Analysis (PCA) for Zhanjiang Mangrove National Nature Reserve (ZMNNR), China.

Tree Height	PC1	PC2	PC3
<i>Aegiceras corniculatum</i>	−1.536	0.652	−0.193
<i>Avicennia marina</i>	0.758	0.979	1.361
<i>Bruguiera gymnorrhiza</i>	−0.791	−1.506	0.206
<i>Kandelia obovata</i>	−1.171	−0.537	1.228
<i>Rhizophora stylosa</i>	1.314	−1.187	0.201
Variation explained (%)	35	28	18
Cumulative proportion (%)	35	63	81
Density			
<i>Aegiceras corniculatum</i>	1.484	−0.399	0.676
<i>Avicennia marina</i>	0.855	0.516	−1.608
<i>Bruguiera gymnorrhiza</i>	−1.549	−0.214	0.094
<i>Kandelia obovata</i>	−0.731	−1.371	−0.763
<i>Rhizophora stylosa</i>	−0.793	1.493	0.049
Variation explained (%)	39	27	18
Cumulative proportion (%)	39	66	77
Basal area			
<i>Aegiceras corniculatum</i>	1.643	−0.154	−0.146
<i>Avicennia marina</i>	0.037	1.391	−1.194
<i>Bruguiera gymnorrhiza</i>	−1.565	−0.762	0.037
<i>Kandelia obovata</i>	−0.312	−0.959	−1.582
<i>Rhizophora stylosa</i>	−1.139	1.133	0.133
Variation explained (%)	35	25	20
Cumulative proportion (%)	35	60	80

3.2. Differences of Mangrove Spatial Distribution at the Species and Sites Level

Mangrove species showed different distributional patterns between Site 1 and Site 2 at the ZMNNR (Table 2). Except *K. obovata*, all dominant species were available in both Sites, but not necessarily matched the same original or non-original stands. In the original and non-original stands of Site 1, both *A. corniculatum* and *R. stylosa* were observed. In Site 2, *A. corniculatum* was absent from original stands and present only in non-original stands, whereas *R. stylosa* was detected only in the original stands. *K. obovata* was restricted to both original and non-original stands of Site 1. *Bruguiera gymnorrhiza* can be found in the original stands of both Sites but only in the non-original stands of Site 1. Finally, *A. marina* was found in the non-original stands of both Sites but not the original stands (Table 2, Figures 6–8).

The average stem diameter for all species in the original mangrove stands ($\bar{\varnothing}$: 0.14 cm) was not significantly higher than that in the non-original stands ($\bar{\varnothing}$: 0.11 cm) (ANOVA, $F = 0.09$, $p = 0.76$). However, the difference in average stem diameter was significant at the species level for *B. gymnorrhiza* (ANOVA, $F = 5.52$, $p = 0.02$), *R. stylosa* (ANOVA, $F = 4.10$, $p = 0.04$) and *A. marina* (ANOVA, $F = 11.68$, $p = 0.04$). Similarly, the mean tree height variations of different species in original and non-original mangrove stands are significant (Figure 6, and Tables 2 and 3). Whereas *R. stylosa* and *K. obovata* showed to be significantly taller in the original stands, *A. corniculatum* and *B. gymnorrhiza* showed non-significant height differences between stands (Table 3). In terms of stem density (Figure 7), the highest estimates were found along creeks and channels regardless of the original or non-original vegetation and regardless of species. The basal area was significantly higher in the original (largely contributed by *B. gymnorrhiza*) as opposed to non-original (contributed by *A. marina*) mangrove stands (Figure 8, Table 3).

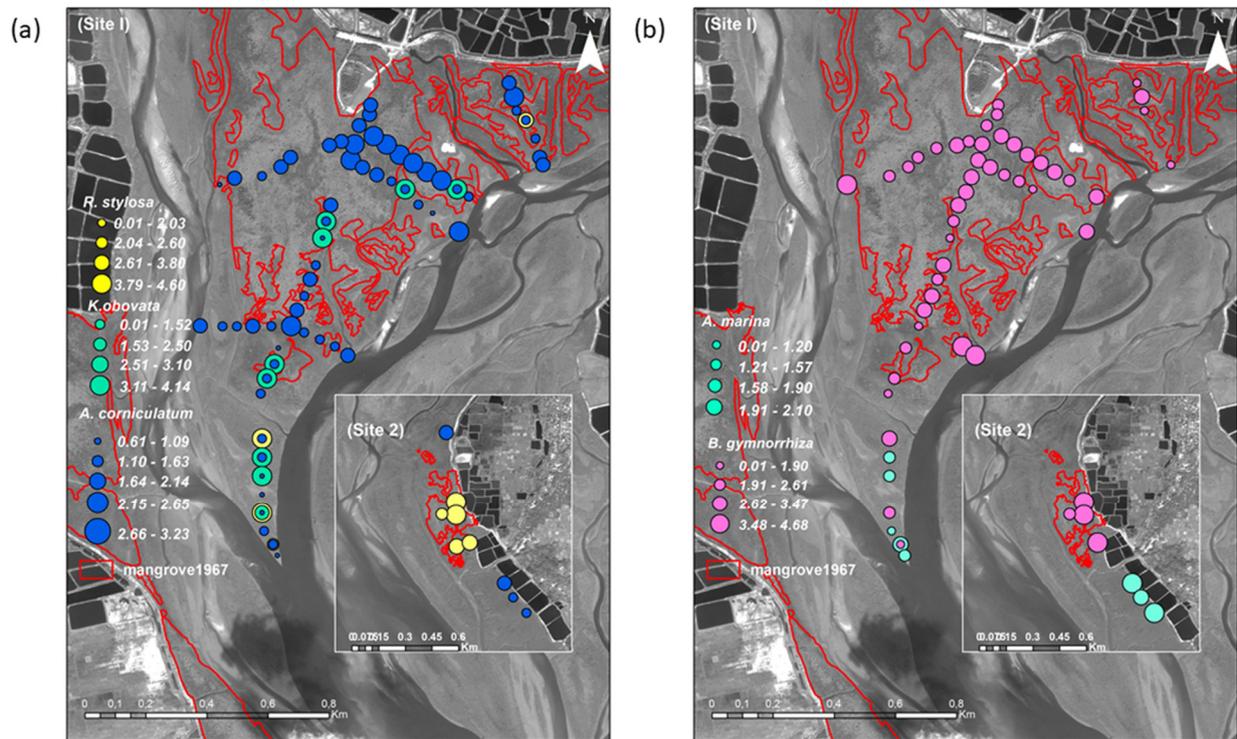


Figure 6. Mean tree height (m) variation of different mangrove species at the Zhanjiang Mangrove National Nature Reserve (ZMNNR), China; (a) *Rhizophora stylosa*, *Kandelia obovata* and *Aegiceras corniculatum*; (b) *Avicennia marina* and *Bruguiera gymnorrhiza*. Species selection for each figure is to avoid bubbles overlapping.

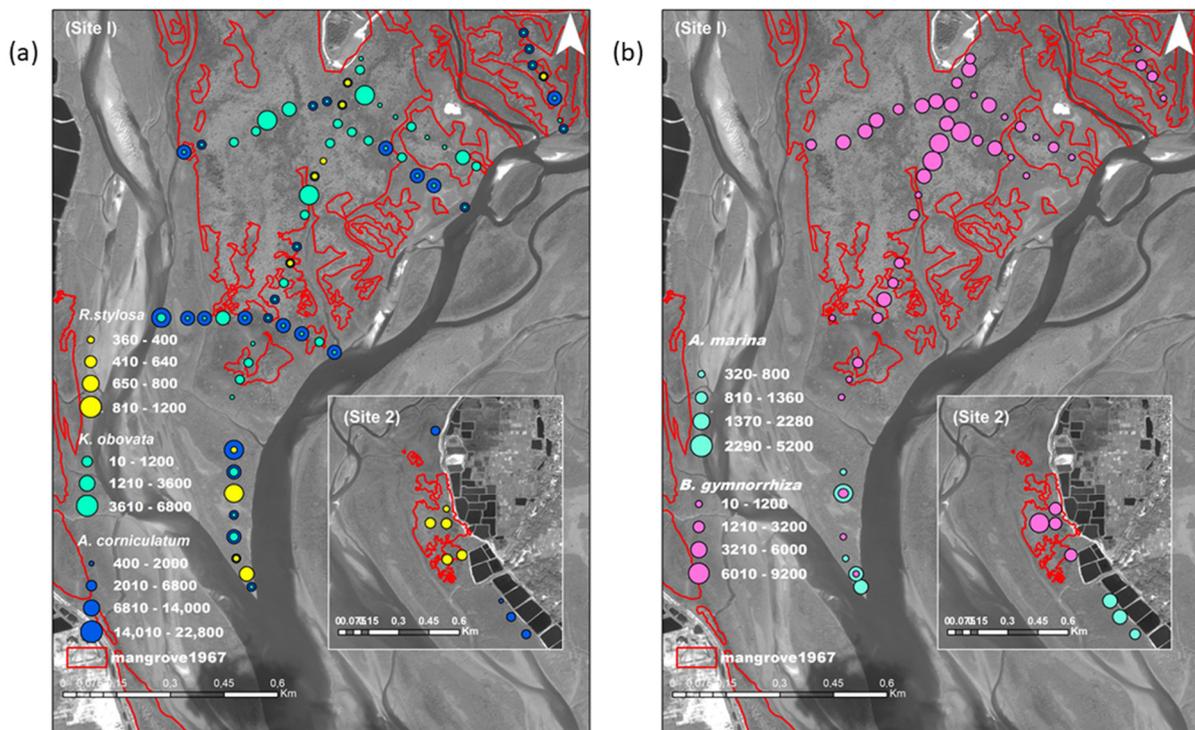


Figure 7. Total stem density (nos. ha⁻¹) of different mangrove species at the Zhanjiang Mangrove National Nature Reserve (ZMNNR), China; (a) *Rhizophora stylosa*, *Kandelia obovata* and *Aegiceras corniculatum*; (b) *Avicennia marina* and *Bruguiera gymnorrhiza*. Species selection for each figure is to avoid bubbles overlapping.

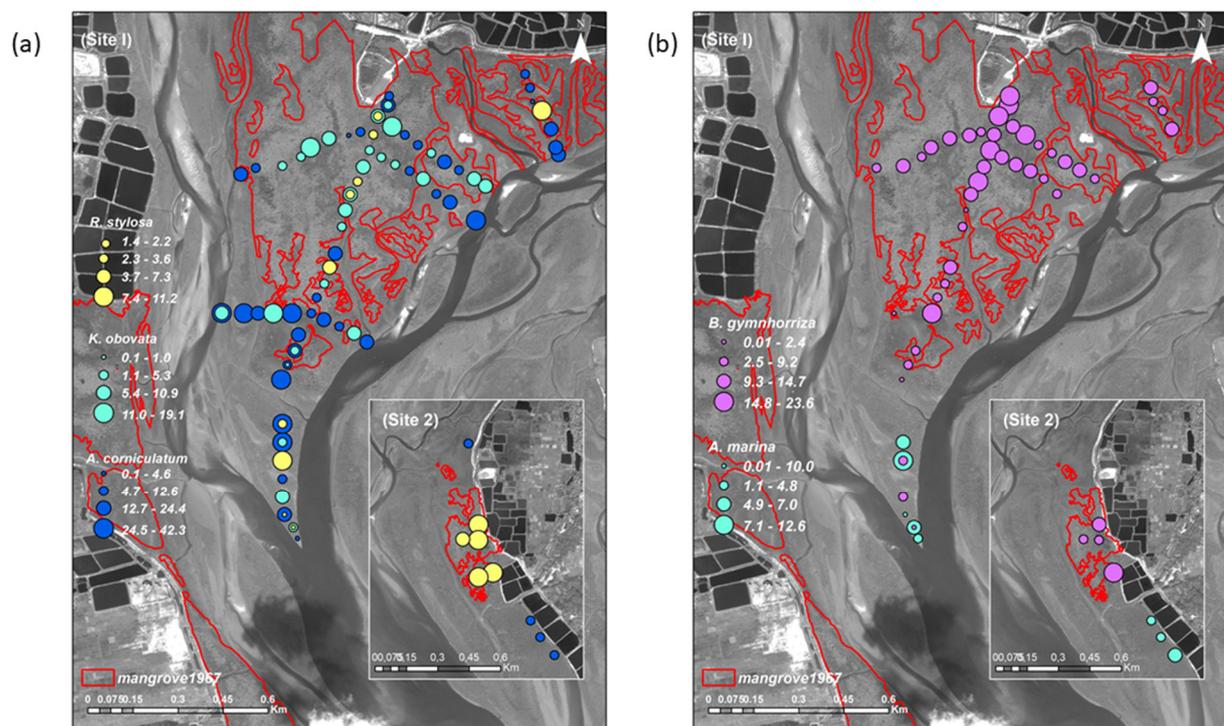


Figure 8. Total basal area (m² ha⁻¹) of different mangrove species at the Zhanjiang Mangrove National Nature Reserve (ZMNNR), China; (a) *Rhizophora stylosa*, *Kandelia obovata* and *Aegiceras corniculatum*; (b) *Avicennia marina* and *Bruguiera gymnorhiza*. Species selection for each figure is to avoid bubbles overlapping.

4. Discussion

4.1. Distinction of Original and Non-Original Stands

The relevance of having original mangrove conservation is to foster greater genetic diversity compared to plantations [77], along with preserving faunal communities [78,79], which need to be considered as an essential element for functionality of the mangrove forest, along with tree parameters [80,81]. Continued monitoring of original and non-original mangrove stands is important for future restoration schemes. In this context, the declassified Corona satellite image proved highly advantageous to identify original stands, particularly where open-source image datasets (e.g., Landsat) are only available from the 1970s onwards and have lower spatial resolution, which are less or not effective on longer-term (≥ 45 years) ecological and restoration research (Table 1). Restoration schemes will not change the disturbed forests back to their original state, the original forests remain a good reference and possible target for regeneration efforts [82,83], given that the environmental conditions do not change significantly.

The proposed non-intrusive method in the present study revealed significant tree structural differences between original and non-original mangrove stands. However, depending on the measured vegetation parameters, there are some exceptions from multi-comparison tests (post hoc Wilcoxon rank sum test). For instance, *Aegiceras corniculatum* and *Rhizophora stylosa* were highly variable and abundant, regardless of their confinement to original or non-original stands, which might explain both their positive and negative eigenvalues along both axes of the PCA (Table 4, Figures 3–5). Similarly, the higher value of the Complexity Index in non-original stands in Site 2 contributed by highest density (507 stems ha⁻¹) of *A. corniculatum* and *A. marina* (Table 2) may explain plots clustering at the intersection (Figures 3–5). In general, there were lower values for tree height, density and basal area estimates in original stands as opposed to non-original stands. Clustering analysis (through PCA, etc.) has previously been used to detect genetic variance, original forest and vegetation characteristics [82,84,85], environmental parameters or faunal communities [86,87]. Further advantages and limitations of the present methodological

approach with respect to GIS, remote sensing and statistical analyses were provided in Table 5.

Table 5. Advantages and limitations of the present methodological protocol identifying original and non-original mangrove stands at the Zhanjiang Mangrove National Nature Reserve (ZMNRR).

Technique	Advantage	Limitation
GIS	<ul style="list-style-type: none"> On-screen digitization: higher reliability to delineate contours for longer time gaps since they may be wider separated e.g., +42 years. 	<ul style="list-style-type: none"> Mutual geo-referencing of images is not highly accurate for natural areas if there are no clearly recognizable landmarks.
Remote sensing	<ul style="list-style-type: none"> Local knowledge on the position of original vegetation highly unreliable. Very high spatial resolution images like GeoEye-1, IKONOS, etc., have been found to be more appropriate for visual interpretation [83]. Non-intrusive [88]. Less input in fieldwork expenses e.g., cost and time saving. Most suitable for distinction of putative visible original and older growth forest. 	<ul style="list-style-type: none"> Satellite images are unavailable for some areas. High technical skills required to improve low spatial and spectral resolution images [89]. Not suitable to study forest succession that started before the first air-borne/space-borne imagery [90]. Low and sparse vegetation over sandy areas may render plants visible or not visible at all [91].
Kruskal–Wallis-PCA-ordination	<ul style="list-style-type: none"> Data transformation corrects for heteroscedasticity which improves clustering capabilities. Useful at separating sites for areas with diverse characteristics in forests structure (Souza et al., 2012). Ordination methods are relatively easy to implement. 	<ul style="list-style-type: none"> Vegetation homogeneity decreases similarity among plots. Axis-1 and 2 do not account 100% variation. Limitations of ordination methods could be overcome with machine learning methods with higher clustering capabilities.

4.2. Characteristics Affecting Mangrove Zonation

Mangrove species distribution at the ZMNRR generally coincides with the zonation patterns in the larger context of Yingluo Bay of South China [66], of which ZMNRR is part. Just like in Yingluo Bay, *A. corniculatum* and *Avicennia marina* were also found in the lower intertidal areas while *Bruguiera gymnorrhiza* and *R. stylosa* occupied the mid-intertidal landward areas (cf. Chen et al., 2018a; Zhang et al., 2006) [90,92]. The dominant species also showed specific assemblages such as *A. corniculatum* + *A. marina* and *R. stylosa* + *B. gymnorrhiza* [90]. Such consistent zonation within a single mangrove bay is, however, not universal, as it has been shown to vary significantly depending on the exact location of the transect [93]. The observed population dynamics (Figures 6–8) suggest physical factors, e.g., floating properties, light availability or physical barriers, may influence mangrove species distribution [94]. In the ZMNRR, the dense pneumatophores of *A. marina* are likely to prevent *Kandelia obovata* propagules from its rooting on the ground and are thus carried away by the tidal waters [92]. This may force *K. obovata* to disperse to other locations as evident from its absence in Site 2. *Bruguiera gymnorrhiza* in original stands may have

obstructed light availability to new seedling growth, and its dense canopy could have prevented itself from colonizing farther located areas [94].

The tall stands of *B. gymnorrhiza* and *R. stylosa* within original stands could exemplify their position as mature species typical of late successional stages [90]. Climax vegetations composed of these species have been reported throughout the Indo West Pacific and Atlantic East Pacific regions [80,95]. In contrast, *K. obovata* is suggested as transitional species in the mangrove forest succession [96,97]. The higher abundance of *A. corniculatum* (with its importance value = 1) in both original and non-original stands suggest a ubiquitous occurrence of this species in the ZMNNR, i.e., it is present in both original and non-original stands. Additionally, *R. stylosa* was observed to coexist with *A. marina* in the non-original stands, specifically in Site 1. The possibility to observe differential stem densities in *A. marina* is corroborated by its tolerance to a wide range of salinities and its response to sedimentation [98–100], which in ZMNNR is influenced by the freshwater discharge from Ximi and Qaoqiao rivers into Yingluo Bay [62]. Besides the absence of *A. marina* in original mangrove stands, its higher density in non-original stands illustrates its pioneering role [101,102]. Stem density was reported to increase during the early stages of forest development and drops over time [103,104]. This is particularly true for *K. obovata*, *B. gymnorrhiza* and *R. stylosa* in the original stands [90], without any natural recruitment of the former two species (pers. obs.). This personal observation is important, since distinguishing original older-growth trees depends on the proper visualization and identification of past images, i.e., Corona images show thick black areas (spots) where older-growth stands/canopies are, and saplings which may be present in original stands could not be easily observed/distinguished. This observation suggests species located in original stands may not continue to populate those areas in the mid-term future (next 45 years, i.e., the same as our study interval but projected in to the future).

The present study confirms the stands in the original mangrove stands as being in a late successional stage and better preserved than the non-original mangrove stands (Tables 2 and 5). Higher sedimentation among the original stands must have been facilitating the growth of *R. stylosa*, and *B. gymnorrhiza*. The present observations are in line with the report of Chen et al. (2018) suggesting mangroves in the ZMNNR are in different successional stages. Long-term analysis on the forest structure would be able to reveal more changes, especially in terms of species composition and distribution [90], but this is not possible with two remote sensing datasets 42 years apart, and is beyond the scope of this paper. Meanwhile, land conversion activities (to agriculture and aquaculture practices), parasites (barnacle infestation), herbivorous crabs [105], etc., might have affected the prevalence of some mangrove species [62]. In this context, specific barriers affecting hydrodynamics and mangrove propagule dispersal should be identified [94].

4.3. Restoration Activities and Future Research

To mitigate the effects of mangrove loss, several management schemes and restoration projects have already been initiated [106], especially in South and Southeast Asia, by both government and non-government organizations [107–109]. Most of these restoration projects endorse silviculture as the principal practice, with coastal stabilization and environmental remediation as the main objectives [110]. However, many rehabilitation projects failed because of inappropriate planting protocols [111,112]. In the case of ZMNNR, the mangrove cover decreased by 51.8% during 1970s and then increased 15% with the plantation schemes from 1990 to 2009 [15,62]. It is worth recalling that these plantation schemes with non-native and invasive mangrove species are known to go at the expense of ecosystem functionality and have no guarantee for success [98,113,114]. In addition, temporal and spatial details of the plantations can be obtained from remote sensing data, which is useful to determine the age of forests accurately [41,46,115]. However, even with thorough mangrove management plans, it is difficult to guarantee field activities are carried out effectively. In Matang Mangrove Forest Reserve (Malaysia), for instance, supervised clearcutting is often done a few years after the tentative years indicated in the management

plan [41] and the activity of clear-cutting a forest concession of 2.2 ha may take up to 2 years [46]. Unfortunately, the local authorities at the ZMNRR do not even have such documented forestry records to compare between present and past studies, and future studies for that matter.

The original mangrove stands in the ZMNRR should be at center of future conservation projects, as the core mangrove area identification benefits the conservational planning at various protection levels [48,49]. Mangrove restoration projects are to be carried out by understanding the current spatial distribution of original/non-original stands, species composition and distribution patterns. The present remote-sensing-based and fieldwork driven methodological framework can be applied to conservation and management of the ZMNRR and can be beneficial to various mangrove ecological research works (including conservation genetics) (Tables 1 and A2). Regarding the remote sensing aspect, an integrated diachronic and up-to-date (high-resolution) image analyses would be able to reveal distinct spectral characteristics of the mangrove species in both original and non-original stands (cf. Otero et al., 2019). Further research using time-series satellite datasets, machine learning and deep learning algorithms, dendrochronological studies (e.g., cambial growth, annual ring growth and vessel densities), can provide more scientific insights in relation to the forest age, etc. [116,117]. The presented methodology may be applied in other locations and further developed to benefit benchmarking ecological research realm and serves as supportive information to the decision-making process in conservation and restoration.

5. Conclusions

The present methodological framework enabled us to distinguish original from non-original mangrove stands with significant differences found in the structural parameters. In general, tall stands with a higher density and basal area were characteristic of the original mangrove as opposed to non-original stands at the ZMNRR. Due to the lack of historical records, it is not possible to provide more insights on the changes in terms of local species composition/distribution and the planted areas of 1990. The described non-intrusive methodology has shed light on further ecological research opportunities (including conservation genetics), along with baseline data for appropriate conservation and management in the ZMNRR.

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Appendix A

Table A1. Classification of sampled plots according to their grouping by the PCA. Coincidental plots for the three vegetation parameters were highlighted in bold.

Vegetation Parameter	Original	Intersection	Non-Original
Height	2, 4, 6, 8, 13, 22, 25 , 28, 31, 32, 33, 36 , 37, 41, 46 , 55 , 57 , 59 , 67 , 68 , 69 , 70 , 71 ,	1, -3, 7, 10, —, 13, 14, 15, 16, 17, —, 20, 21, 26, 34, 35, —, 38, 39, 40, —, 44, —, 47, —53, —, 55, —, 61, —65, 67	9, 11, 12, —, 18, 19, 23, 24, —27, —29, 30, 31, —42, 43, —45, —, 48, 49, 50, 51, 52, —54, 55, 56, —60, 62, 63, —64, —66, —72, —, 73, 74, 75, 76
Density	1, 2, 3, 4, 5, 6, —, 8, 9, 10, —, 12, —, 17, —, 27, 28, 29, 30, 31, —, 35, 36, 37, 38, 39, —, 46, —, 67, 68, 69, 70, 71.	7, —, 13, —, 15, 16, 18, —, 32, 33, 34, —, 40, —, 44, 45, —47, 48, 49, —, 51, —, 56, —, 58, 59, —, 64, 65.	11, —, 14, —16, —, 18, 19, 20, 21, 22, 23, 24, 25, 26, —, 36, 37, 39, —, 41, 42, 43, —, 50, —, 52, 53, 54, 55, —, 57, —, 60, 61, 62, 63, —66, —, 72, 73, 74, 75, 76.
Basal area	1, 2, 3, 4, 5, 6, 7, 8, 12, —, 22, 23, 25, 28, 36, 46, 58, 59, 67, 68, 69, 70, 71,	9, 10, 11, —13, 14, 15, 16, 17, 18, 19, 20, 21, —24, 26, 27, 29, 30, 31, 32, 33, 34, 35, 37, 38, 39, 40, 41, 42, 43, 44, 45, 47, 48, 49, 51, 52, 53, 54, 56, 62, 63, 64, 65, 66,	50, 55, 57, 60, 61, 72, 73, 74, 75, 76

Table A2. Specific recommendations for genetic sampling.

- Genetic differentiation varies between original vs. non-original stands. Studies on genetics and epigenetics based on tree height and stem diameter showed significant differences regarding forest nature [87].
- Geographic gradients of genetic diversity could be highly important in maintaining genetic diversity through gene flow [118]. For example, genetic differences between original stands may be analyzed for climax *B. gymnorrhiza* and *K. obovata* in Sites 1 and 2 which have Gaoqiao river as a natural barrier. Is the Gaoqiao River a barrier against gene flow for climax species *B. gymnorrhiza* or *R. stylosa*? If so, *R. stylosa* and *B. gymnorrhiza* colonize Site 2 starting from Site 1, hypothesizing genetic material spreads from Site 1 to Site 2. On a wider scale, it would be useful to check if the propagules and seedlings from original stands disperse to other ZMNNR locations or neighboring provinces.
- Studies of the vegetation structure on seaward location are suggested as plant density is an important demographic factor affecting mating systems. Mangrove species have correlated with density negatively as well as positively [119]. For instance, outcrossing species combine high rates of sexual reproduction with high amounts of propagule dispersal [120], which might explain *B. gymnorrhiza* presence in both original and non-original stands. Research should check what type of correlation between density and out-crossing rate exists in the ZMNNR and the Leizhou Peninsula.
- Sampling should be accompanied with collection of environmental data (i.e., salinity, soil type, etc.). The restoration success is eventually measured by parameters, others than mangrove cover increase, i.e., vegetation structure (i.e., height, basal area and density), arthropods diversity (e.g., crabs) with a comparable reference site with no degradation on the ecological processes [50,112]
- Studies could be focused on other nearby locations, e.g., Techeng, Beitan and Lindong because some areas may have even lost all original mangroves. Triest (2008) reported the clearance of mangrove to threaten sufficient gene diversity in out-crossing or mixed mating species. Investigations should be done across patches of stands on the Leizhou peninsula, to identify any connection between eastern and western genetic flows.

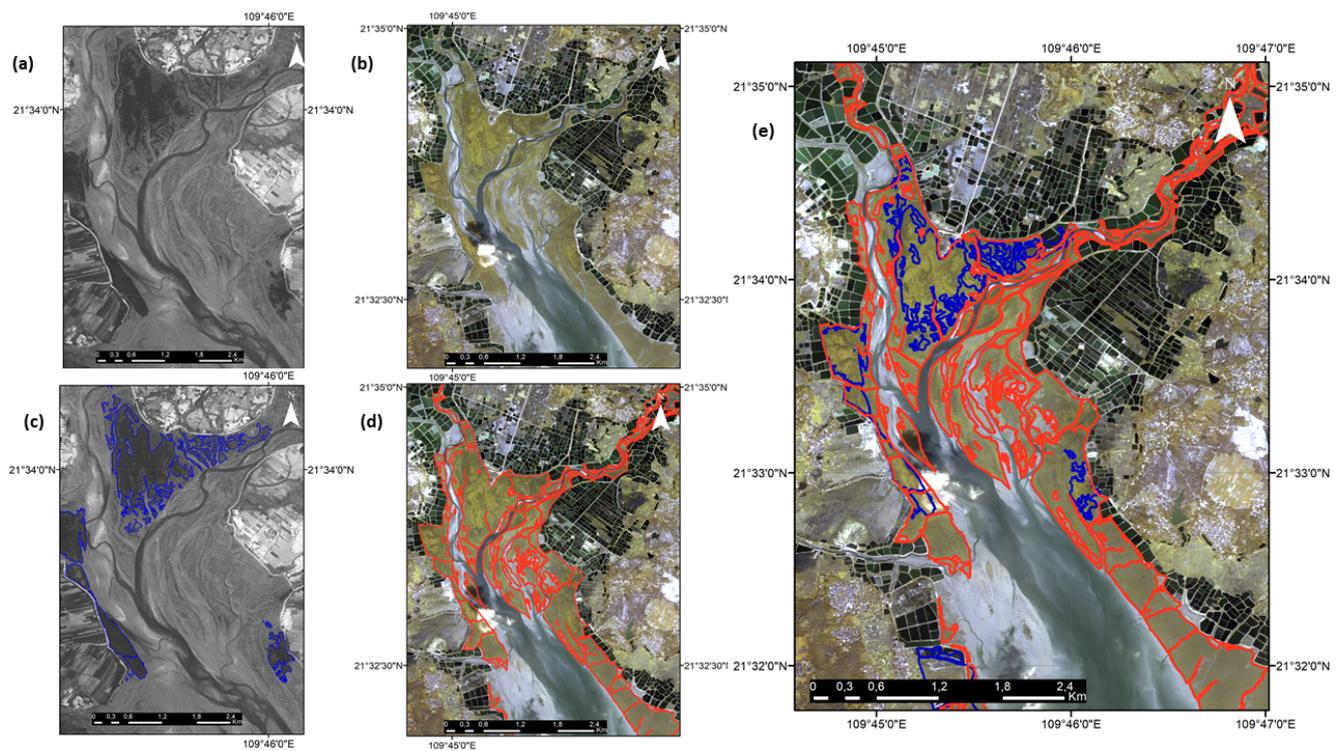


Figure A1. Raw satellite images used for this study; (a) The extent of ZMNNR mangrove as observed from Corona KH-4B satellite imagery dated 17 Dec 1967; (b) The extent of ZMNNR mangrove cover observed on GeoEye-1 satellite image dated 16 Oct 2009; (c) The on-screen digitized blue polygon on original late community mangrove observed on Corona KH-4B satellite imagery; (d) The on-screen digitized red polygons on mangrove forest observed on GeoEye-1 satellite image; (e) Overlaid on-screen digitized polygons of mangrove as observed in 1967 (blue) and 2009 (blue) satellite datasets.



Figure A2. False colour composite using bands R = 4; G = 3; B = 2 on the pansharpened GeoEye-1 image.

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