Status of the undisturbed mangroves at Brunei Bay, East Malaysia: a preliminary assessment based on remote sensing and ground-truth observations

Behara Satyanarayana[1,2,*], Aidy M. Muslim[1,*], Nurul Amira Izzaty Horsali[1], Nurul Ashikin Mat Zauki[1], Viviana Otero[2], Muhammad Izuan Nadzri[1], Sulong Ibrahim[1], Mohd-Lokman Husain[1] and Farid Dahdouh-Guebas[2,3]

[1] Universiti Malaysia Terengganu—UMT, Mangrove Research Unit (MARU), Institute of Oceanography and Environment (INOS), Kuala Terengganu, Malaysia
[2] Université Libre de Bruxelles—ULB, Laboratory of Systems Ecology and Resource Management, Brussels, Belgium
[3] Laboratory of Plant Biology and Nature Management, Vrije Universiteit Brussel, Brussels, Belgium
[*] These authors contributed equally to this work.

ABSTRACT

Brunei Bay, which receives freshwater discharge from four major rivers, namely Limbang, Sundar, Weston and Menumbok, hosts a luxuriant mangrove cover in East Malaysia. However, this relatively undisturbed mangrove forest has been less scientifically explored, especially in terms of vegetation structure, ecosystem services and functioning, and land-use/cover changes. In the present study, mangrove areal extent together with species composition and distribution at the four notified estuaries was evaluated through remote sensing (Advanced Land Observation Satellite—ALOS) and ground-truth (Point-Centred Quarter Method—PCQM) observations. As of 2010, the total mangrove cover was found to be ca. 35,183.74 ha, of which Weston and Menumbok occupied more than two-folds (58%), followed by Sundar (27%) and Limbang (15%). The medium resolution ALOS data were efficient for mapping dominant mangrove species such as *Nypa fruticans*, *Rhizophora apiculata*, *Sonneratia caseolaris*, *S. alba* and *Xylocarpus granatum* in the vicinity (accuracy: 80%). The PCQM estimates found a higher basal area at Limbang and Menumbok—suggestive of more mature vegetation, compared to Sundar and Weston. Mangrove stand structural complexity (derived from the complexity index) was also high in the order of Limbang > Menumbok > Sundar > Weston and supporting the perspective of less/undisturbed vegetation at two former locations. Both remote sensing and ground-truth observations have complementarily represented the distribution of *Sonneratia* spp. as pioneer vegetation at shallow river mouths, *N. fruticans* in the areas of strong freshwater discharge, *R. apiculata* in the areas of strong neritic incursion and *X. granatum* at interior/elevated grounds. The results from this study would be able to serve as strong baseline data for future mangrove investigations at Brunei Bay, including for monitoring and management purposes locally at present.

INTRODUCTION

A combination of ground truth and remote sensing data analysis is advantageous for developing the most reliable land-use/cover mapping and thereby useful for making appropriate decisions for conservation and management of natural resources (*Kovacs, Wang & Blanco-Correa, 2001*; *Kovacs et al., 2004*; *Chauhan & Dwivedi, 2008*; *Neukermans et al., 2008*; *Satyanarayana et al., 2011*; *Leempoel et al., 2013*). In the case of mangroves, remote sensing data have become indispensable due to its time saving and cost-effective nature compensating for the fieldwork, which is often difficult to carry out, especially in areas of low accessibility (*Giri et al., 2007*; *Dahdouh-Guebas & Koedam, 2008*; *Giri et al., 2008*; *Massó i Alemán et al., 2010*; *Giri et al., 2011*; *Satyanarayana et al., 2011*; *Cárdenas, Joyce & Maier, 2017*). Mangrove mapping—as per the target of identifying different vegetation details—has been conducted with low to very high-resolution spaceborne (e.g., Landsat, IKONOS, QuickBird, GeoEye-1) and airborne remote sensing data (*Dahdouh-Guebas et al., 2000*; *Sulong et al., 2002*; *Wang et al., 2004*; *Seto & Fragkias, 2007*; *Giri et al., 2008*; *Dahdouh-Guebas & Koedam, 2008*; *Spalding, Kainuma & Collins, 2010*; *Giri et al., 2011*; *Hansen & Loveland, 2012*; *Leempoel et al., 2013*; *Proisy et al., 2016*). Also, the potential of moderate resolution data like Advanced Land Observation Satellite (ALOS) and Sentinel for mangrove studies is well recognised (*Hartoko et al., 2015*; *Castillo et al., 2017*; *Chen et al., 2017*). The optical remote sensing data which were often limited by cloud cover to study mangrove ecosystems have been compensated through the radar and drone imageries in recent years (*Walters et al., 2008*; *Cornforth et al., 2013*; *De Santiago, Kovacs & Lafrance, 2013*; *Kovacs et al., 2013*; *Hamdan, Khali Aziz & Mohd Hasmadi, 2014*; *Lucas et al., 2014*; *Jhonnerie et al., 2015*; *Aslan et al., 2016*; *Tian et al., 2017*). Similarly, there are several plot-based and plot less methods which exist for undertaking vegetation inventories (*Elzinga et al., 2001*). Among others, the Point-Centred Quarter Method (PCQM) is recognised as the most appropriate ground-truth for mangrove and remote sensing combinatory investigations (*Cintrón & Schaeffer Novelli, 1984*; *Dahdouh-Guebas & Koedam, 2006*; *Satyanarayana et al., 2011*). The PCQM is not only efficient for characterising mangrove vegetation and less time-consuming, but it also causes minimum damage to the understorey while sampling (*Cunningham, 2001*; *Dahdouh-Guebas & Koedam, 2006*).

The mangrove forest in Malaysia (709,700.00 ha) is the second largest in Southeast Asia and sixth (after Indonesia, Brazil, Australia, Mexico and Nigeria) among the nations that supporting highest mangrove cover in the world (*Spalding, Kainuma & Collins, 2010*; *Hamdan et al., 2012*). East Malaysia (i.e., Sabah and Sarawak) is supporting up to 84% of the country's mangroves and West (Peninsular) Malaysia the remaining 16% (Table 1). Mangroves at Brunei Bay are jointly shared, but separately administered by East Malaysia and Brunei Darussalam (Fig. 1). Although known as one of the largest tracts of relatively undisturbed forest in eastern Asia (*Brunei Darussalam Forestry Department, 2010*), the

Table 1 **Mangrove cover in Malaysia.** State-wise distribution of mangrove cover in West (Peninsular) and East Malaysia (source: *Hamdan et al., 2012*).

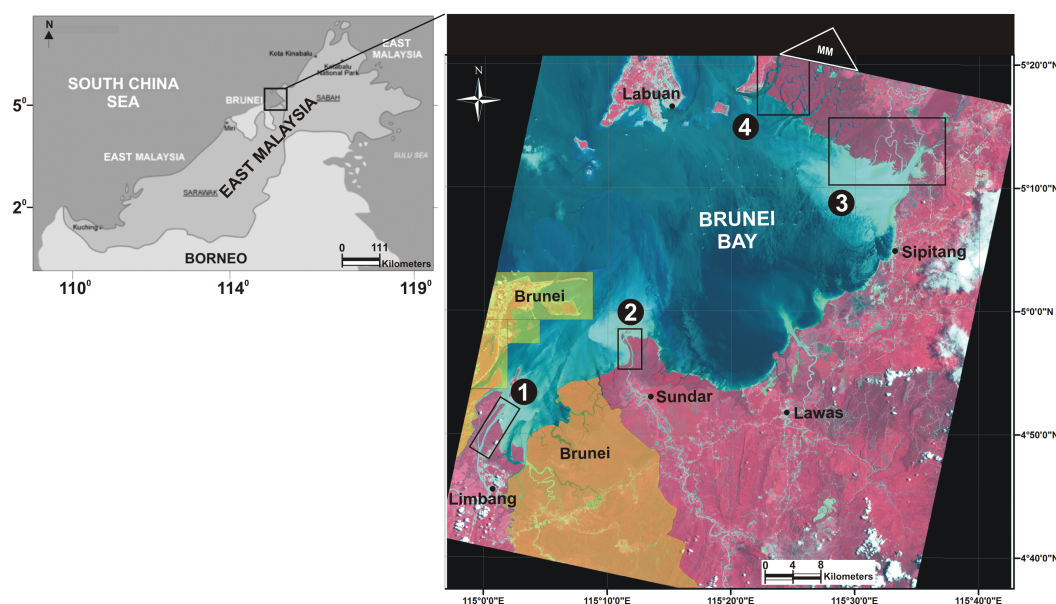|	State	Mangrove cover (ha)	% contribution
1. Peninsular (West) Malaysia			
West coast:	Perak	43,291.97	
	Johor	23,676.43	
	Selangor	22,530.20	
	Kedah	7,841.25	
	Negari Sembilan	2,276.50	
	Pulau Pinang	1,695.60	
	Melaka	1,308.68	
	Perlis	94.02	
Total West coast:	–	**100,438.15**	**14.15**
East coast:	Pahang	9,039.26	
	Terengganu	2,925.74	
	Kelantan	428.95	
Total East coast:	–	**12,393.95**	**1.75**
2. East Malaysia	Sabah	426,334.20	
	Sarawak	170,533.70	
Total East Malaysia	–	**596,867.90**	**84.10**
	Total	**709,700.00**	**100.00**

mangroves at Brunei Bay have been less scientifically explored and much of the information on vegetation structure, ecosystem services and functioning, and land-use/cover changes is confined to grey literature (e.g., *Justin, 2007*; *Ali & Mohd Ariff, 2007*; *Malaysian Ministry of Natural Resources and Environment, 2014*). According to *Adiana et al. (2017)*, there were only five scientific publications between 1968 and 2012 on Brunei Bay, and they related to water pollution and marine mammals in the area. The research works after 2012 (e.g., *Alkhadher et al., 2015*; *Joseph et al., 2016*; *Proum et al., 2016*; *Joseph et al., 2017*) also focused on sediment pollution and sea turtles, but none were specific to the (Malaysian) mangrove vegetation.

The present study was primarily aimed at identifying the current status of the Malaysian mangrove cover at Brunei Bay. The objectives were to develop a species-level classification map based on remote sensing (ALOS) data for Limbang, Sundar, Weston and Menumbok estuaries adjoining Brunei Bay, and to integrate and validate the findings through ground-truth (PCQM) observations.

MATERIALS AND METHODS

Study area

Brunei Bay is extended over 2,500 km^2 where much of its aquatic and terrestrial land belongs to East Malaysia (Fig. 1). The bay area is also known as a significant habitat for marine biological diversity in the South China Sea (*Vo, Pernetta & Paterson, 2013*; *Joseph et al., 2016*). The southern limit of the bay is flanked by lush green mangroves, especially on the

Figure 1 Study area location. Location of Brunei Bay in the East Malaysia. The mangrove floristic surveillance was carried out from four major estuarine areas namely, Limbang (box 1), Sundar (box 2), Weston (box 3), and Menumbok (box 4). The town/village names in the vicinity of Brunei Bay were represented by black bullets. The area under the jurisdiction of Brunei Darussalam was masked in yellow colour (ALOS satellite image dated 1 Sept 2010). The white triangle named after MM on the satellite image shows the location of missing mangrove patch on the northernmost corner of Menumbok estuary.

Full-size ☑ DOI: 10.7717/peerj.4397/fig-1

lower reaches of Limbang, Sundar, Weston and Menumbok rivers (*BirdLife International, 2015*). The Limbang estuary—emerging from the three rivers, namely Sungai Manunggul, Sungai Limbang and Sungai Pandaruan—is orientated in a north-south direction whereas the Sundar estuary—emerging from Sungai Trusan—is stretched between Kuala Trusan and Tanjung Perepat in a west-east direction. Both Weston and Menumbok estuaries are formed by Sungai Padas and Sungai Klias, respectively, and run in a north-east direction. The mangrove vegetation, together with seagrass beds and coral reefs in Brunei Bay, are providing several eco-socio-economic benefits to the local communities (*Ahmad-Kamil et al., 2013*). This study was conducted with the permission of the State Forestry Department of Sarawak (# NCCD.907.4.4 (Jld. 10)-294).

The climate of Brunei Bay is influenced by tropical weather with two monsoonal regimes: northeast (mid-December to mid-March) and southwest (mid-May to the end of October) (*Malik, 2011*). The historical weather data (2005–2015) showed an average highest temperature of 33.5 °C for April–May and the highest precipitation of 72.9 mm for June (*WU, 2015*). Intense seawater current, accompanied by strong winds, can be observed every year during the northeast monsoon (*Nelson et al., 2015*). Monsoonal impact in the areas facing the South China Sea is evident by coastal erosion and in less and patchy distribution of the mangrove cover (*Hamdan et al., 2012*).

Remote sensing data and analysis

For mangrove species-level mapping at Brunei Bay, the Advanced Visible and Near-Infrared Radiometer type 2 (AVNIR-2) data acquired from the ALOS (spatial resolution: 10 m) (dated 1st September 2010) were used. The ALOS data—subjected to both atmospheric and geometric corrections—were provided by the Japan Science and Technology Agency (JST). However, to ensure a good match of the land-use/cover features in the imagery with the ground-truth observations, the data have been georeferenced again with WGS_1984 coordinate system using a toposheet (1:50,000) obtained from the Department of Survey and Mapping Malaysia (RMS error: 0.682) (ArcMap v.10). In order to have a better image processing and analysis, the mangrove areas adjacent to the bay and river channels were digitised on screen. For the medium resolution remote sensing data like ALOS, on screen digitisation through visual interpretation is indeed beneficial to separate mangrove and non-mangrove areas (*Kuenzer et al., 2011*). In this context, the false colour composite (FCC) (with 4-3-2 band combination) of the ALOS data was used to recognise the mangroves visible in a darker shade than of nearby terrestrial vegetation due to less spectral reflectance (*Spalding, Kainuma & Collins, 2010*; *Zhang et al., 2017*). The polygon features, as a new shapefile (with WGS_1984 coordinate system), were created only for mangroves under the jurisdiction of East Malaysia, and extracted the raster cells using spatial analyst tools (with 'extract by polygon' function in ArcMap v.10; ArcGIS, Redlands, CA, USA).

Species-level classification using all four (blue, green, red and near-infrared) bands was carried out through the maximum-likelihood algorithm that known to facilitate a robust classification for mangroves (*Wang, Sousa & Gong, 2004*; *Shafri, Suhaili & Mansor, 2007*; *Satyanarayana et al., 2011*; *Kuenzer et al., 2011*; *Nguyen et al., 2013*; *Khatami, Mountrakis & Stehman, 2016*; *Mafi-Gholami, Mahmoudi & Zenner, 2017*). In this context, the training samples for the most dominant mangrove taxa such as *Nypa*, *Rhizophora*, *Sonneratia* and *Xylocarpus* spp., were assigned based on ground knowledge acquired through the PCQM (68 sample points: Limbang—9, Sundar—19, Weston—20 and Menumbok—20) (details are given in 'Ground inventory'). In addition, tonality and textural characteristics (in FCC) of the dominant species were considered (cf. *Dahdouh-Guebas et al., 2000*; *NRC, 2006*). For instance, *Nypa* vegetation was represented by a dark red colour with coarse texture, whereas *Rhizophora* by bright red with fine texture, *Sonneratia* by light red with open spaces (especially at river mouths), and *Xylocarpus* by a bright red colour with coarse texture (especially at back mangrove area). Based on our ground knowledge and visual interpretation of the satellite data, we assigned 20–25 training samples (with a pixel count of 125,135–572,692) for the widespread mangrove species (*Nypa, Rhizophora* spp.), and 10–15 (with a pixel count of 98,610–102,029) for the locally distributed species (*Sonneratia*, *Xylocarpus* spp.). The classified image was then subjected to an accuracy assessment through a confusion matrix (*Congalton, 1991*), for which 144 additional ground control points (GCPs) (Limbang—60, Sundar—45, Weston—26 and Menumbok—13) collected from both mangrove and non-mangrove areas were used. The GCPs were collected randomly as per the forest condition and accessibility. The location of the GCPs was marked on the ALOS imagery (hardcopy) and recorded the type of land-use/cover (i.e., mangrove or non-mangrove), together with species composition in the case of mangrove, for the
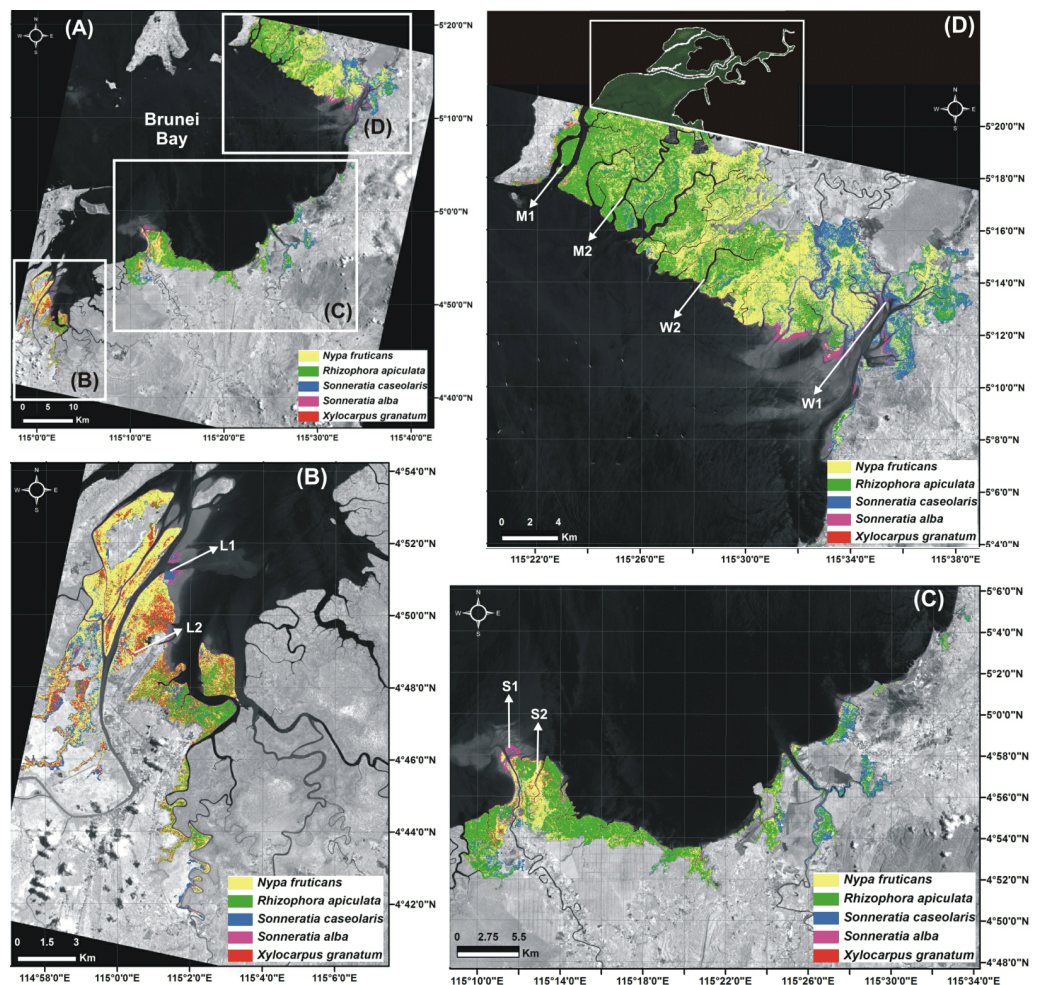
accuracy assessment. Most locations in mangrove from where the GCPs were collected have shown the distribution of dominant species in more than 10 m × 10 m land-cover area.

For the accuracy assessment, we also report *quantity* (%)—the amount of pixels that differed between reference data and classification per class, *exchange* (%)—the allocated error by number of pixels that interchanged between two classes, and *shift* (%)—the other allocation differences that were not included in the *exchange* difference (cf. *Pontius Jr & Millones, 2011*; *Pontius Jr & Santacruz, 2014*). Any disagreements among *quantity*, *exchange* and *shift* variables are useful to learn the sources of error in the classification in a more interpretable manner (*Pontius Jr & Millones, 2011*). Estimates of *quantity*, *exchange* and *shift* were made from the PontiusMatrix41 (Microsoft Excel file) developed by RG Pontius (https://www.clarku.edu/).

Area statistics showing the total mangrove cover (with a species-level demarcation for each estuary) at Brunei Bay were derived from the supervised classification. For this purpose, the mangrove extent was treated under three sectors: Limbang, Sundar (up to Sipitang village) and Weston + Menumbok together (due to no clear-cut mangrove boundary between these two estuaries). However, there were a few limitations identified with the ALOS data. Firstly, the image was four years old at the time of fieldwork. Second, a (minor) patch of mangrove was missing on the northern most corner of Menumbok (Fig. 1). The former concern was evaluated through our ground inventory by observing the mangrove cover changes (if any), while the latter was identified from Google Earth Pro (image dated 29th November 2014) by digitising the missing (mangrove) area.

Ground inventory

For the ground data collection (5th–19th August 2014), two 100 m length transects—one close to the river mouth and another in mid-forest—were chosen from each estuary i.e., Limbang, Sundar, Weston and Menumbok (eight transects in total). Sampling at the river mouth was chosen to identify the pioneer group of vegetation (i.e., mangrove succession by select species), whereas in the mid-forest to identify other available species in the vicinity. We took a 100 m transect in order to cover at least ten sample points with four quadrants of the PCQM (cf. *Engeman et al., 1994*; *Satyanarayana et al., 2002*; *Satyanarayana et al., 2011*). Different adult tree (i.e., ≥ 1.3 m height with a diameter (D_{130}) of ≥ 2.5 cm or girth (G_{130}) ≥ 8 cm) structural parameters such as density (trees 0.1 ha^{-1}), basal area (m^2 0.1 ha^{-1}), relative density (%), relative dominance (%), relative frequency (%), species' importance value (IV) (relative density + relative dominance + relative frequency), and the complexity index (CI) were estimated using the P-DATA PRO *v*. 5.01 interface developed by *Dahdouh-Guebas & Koedam (2006)*. In the case of *Nypa*—as its stem remains underground—the diameter of all leaf shoots was considered to determine the (average) basal area. For mangrove species identification, the nomenclature suggested by *Tomlinson (1986)* and *Duke (2006)* was followed. Each tree height was measured with the help of a clinometer (Suunto PM-5, Finland). A hand-held Global Positioning System (Garmin 45; Garmin, Olathe, KS, USA) was used for navigation and to obtain the latitude and longitude positions of the sampling points.

Figure 2 **Mangrove supervised classification.** (A) Supervised classification of the mangrove vegetation at Brunei Bay. The species-level distribution of mangroves (white boxes) at (B) Limbang, (C) Sundar and, (D) Weston + Menumbok estuaries The arrows named after L1, L2 in (B), S1, S2 in (C) and, W1, W2, M1 and M2 in (D) shows the vegetation survey (PCQM) sampling points at those respective estuarine areas (ALOS single band satellite image dated 1 Sept 2010) (the mangrove area under the jurisdiction of Brunei Darussalam was ignored from image processing/analysis, see Fig. 1 for country's boundary). The white box in (D) shows digitized mangrove cover (from the Google Earth Pro image dated 29 Nov 2014) on the northernmost corner of Menumbok estuary.

Full-size 🖼 DOI: 10.7717/peerj.4397/fig-2

Statistical analysis

Variation between the tree structural parameters, like density and basal area, at Limbang, Sundar, Weston and Menumbok estuaries was tested through one-way ANOVA (OriginPro *v*. 9.1).

RESULTS

Remote sensing based observations

From the supervised classification of the ALOS data (Fig. 2), it was possible to recognise the predominance of *Sonneratia caseolaris* (L.) Engler, *Rhizophora apiculata* Bl. and *Nypa*

Table 2 Accuracy assessment of the supervised classification. Confusion matrix showing the accuracy assessment of species-level mangrove supervised classification at Brunei Bay.

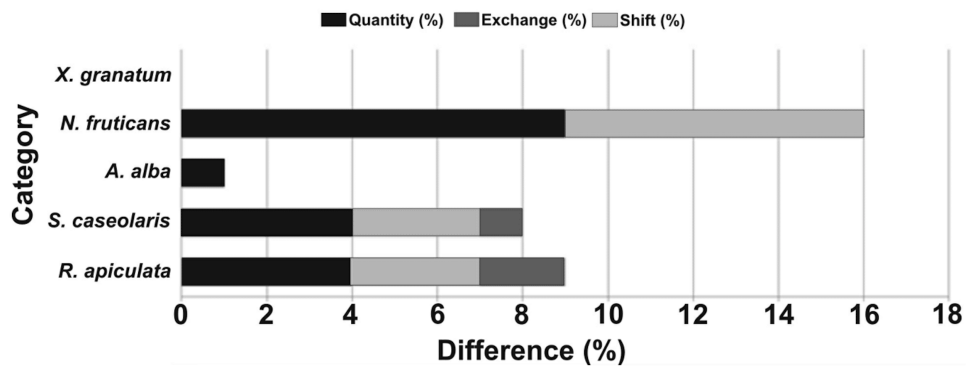| | | Supervised classification | | | | | | |
		R. apiculata	S. caseolaris	S. alba	N. fruticans	X. granatum	Total	Producer's accuracy (%)
	R. apiculata	46	1	2	1	0	50	92
	S. caseolaris	0	12	2	1	0	15	80
Ground-truth	S. alba	0	0	12	0	0	12	100
	N. fruticans	11	6	1	23	0	41	56
	X. granatum	0	0	0	0	5	5	100
	Total	57	19	17	25	5	123	
	User's accuracy (%)	81	63	71	92	100		

Notes.
Genus names: R, *Rhizophora*; S, *Sonneratia*; N, *Nypa*; X, *Xylocarpus*.

fruticans (Thunb.) Wurmb., along with *S. alba* J Smith and *Xylocarpus granatum* König species at Brunei Bay (accuracy: 80% and Kappa index: 0.714) (Table 2). The difference in the amount of pixels between the reference data and the classification per class (= *quantity*) was found to be 9%, whereas the error due to interchanged pixels between two classes (= *exchange*) was 7% and the allocation difference other than to the *exchange* difference (= *shift*) was 1%. Among the five mangrove species, *N. fruticans* showed the highest *quantity* (9%) and *exchange* (7%) differences (Fig. 3). In fact, there was a considerable overlap in the (visible range) spectral reflectance values of the dominant mangrove species (Fig. 4). The Malaysian mangrove cover at Brunei Bay was found to be *ca.* 35,183.74 ha of which Limbang occupied 5,011.42 ha, Sundar (up to Sipitang village) 9,606.46 ha, and Weston + Menumbok 20,565.86 ha (Table 3). If the spatial extent of each mangrove species is considered, *N. fruticans* shows a widespread distribution (14,879.27 ha), followed by *R. apiculata* (12,801.89 ha), *S. caseolaris* (5,533.10 ha), *X. granatum* (993.10 ha) and *S. alba* (976.38 ha) (Table 3). Area wise, Limbang, Weston and Menumbok were dominated by *N. fruticans* (as an important species), and Sundar by *R. apiculata* (Table 3).
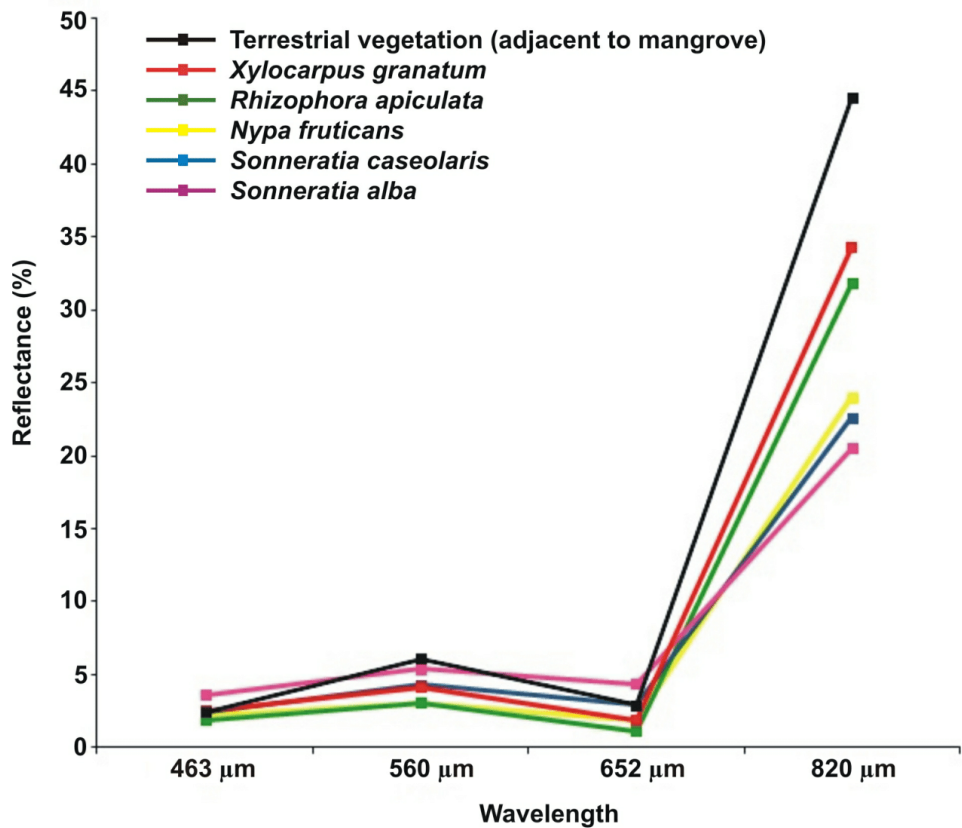
Ground inventory observations

Ground-truth observations found several non-dominant mangrove species like *Avicennia alba* Blume, *Bruguiera gymnorrhiza* (L.) Lamk., *B. cylindrica* (L.) Blume, *Ceriops* sp., *Heritiera littoralis* Dryand and *Kandelia candel* (L.) Druce, along with the associates such as *Acanthus ilicifolius* L., *Acrostichum aureum* L., *Derris trifoliata* Lour. and *Hibiscus tilliaceus* L., in the vicinity. Out of 11 dominant and non-dominant mangrove species, only nine were encountered in the vegetation (PCQM) sampling points (Table 4). Among the four estuaries, Limbang had the highest mangrove basal area (120.17 m^2 0.1 ha^{-1} with a density of 163 trees 0.1 ha^{-1}), followed by Menumbok (81.17 m^2 0.1 ha^{-1} with a density of 132 trees 0.1 ha^{-1}), Weston (35.10 m^2 0.1 ha^{-1} with a density of 130 trees 0.1 ha^{-1}), and Sundar (33.24 m^2 0.1 ha^{-1} with a density of 134 trees 0.1 ha^{-1}). Basal area at Limbang and Menumbok was significantly different from Sundar and Weston (one-way ANOVA, $P = 0.08$). *Sonneratia caseolaris* holds the highest importance value for Limbang, while

Figure 3 **Pontius matrix.** Quantity, Exchange and Shift differences in species-level mangrove supervised classification at Brunei Bay (Genus names: R, *Rhizophora*; S, *Sonneratia*; N, *Nypa* and X, *Xylocarpus*). The *X*-axis refers to the difference (%) in each mangrove category of the study area.

Full-size ⊡ DOI: 10.7717/peerj.4397/fig-3

Figure 4 **Spectral reflectance of mangrove and non-mangrove vegetation.** Average spectral reflectance curves of the dominant mangrove species and the adjacent terrestrial vegetation at Brunei Bay.

Full-size ⊡ DOI: 10.7717/peerj.4397/fig-4

Table 3 Mangrove area. Mangrove area statistics based on supervised classification at the Brunei Bay.

Species	Area (ha)			Total	% contribution
	Limbang	Sundar (up to Sipitang village)	Weston + Menumbok		
R. apiculata	782.45	5,003.25	7,016.19	12,801.89	36.38
S. caseolaris	751.05	1,407.28	3,374.77	5,533.10	15.73
S. alba	169.37	270.11	536.90	976.38	2.77
N. fruticans	2,566.90	2,728.40	9,583.97	14,879.27	42.29
X. granatum	741.65	197.42	54.03	993.10	2.83
Total:	5,011.42	9,606.46	20,565.86	35,183.74	100.00

Notes.
Genus names: R, *Rhizophora*; S, *Sonneratia*; N, *Nypa*; X, Xylocarpus.

R. apiculata for both Sundar and Menumbok, and *N. fruticans* for Weston. The mangrove stand structural complexity (derived from the complexity index) was high in the order of Limbang > Menumbok > Sundar > Weston (Table 4). In terms of the diameter class distribution, more than 50% of trees at Limbang were represented by 31–90 cm (range: 9.5–198.9 cm), Sundar 2.5–40 cm (range: 3.2–186.1 cm), Weston 2.5–60 cm (range: 3.0–190.1 cm), and Menumbok 2.5–120 cm (range: 2.5–250 cm) (Fig. 5).

The ground inventory also revealed no detectable changes in relation to the four-year old satellite (ALOS) data. The core mangroves were found intact in almost all locations between 2010 and 2014. The only sign of change was observed at Limbang, Sundar and Weston river mouths where shrubby vegetation (as understood from the visual interpretation of the ALOS data before the fieldwork) had become grown-up *Sonneratia* trees (height: 9–13 m). The missing mangrove patch (observed from the Google Earth) on the northern most corner of Menumbok was *ca.* 3,741 ha and found to be co-dominated by *R. apiculata* and *N. fruticans* (similar to other mangrove patches at Menumbok).

DISCUSSION

In recent years, remote sensing technology has greatly enhanced our understanding of mangrove ecosystems (*Walcker, Gratiot & Anthony, 2016*). The present study also found several interesting observations about the Malaysian mangrove cover at Brunei Bay. As of 1st September 2010 (ALOS data), the spatial extent of the mangroves was 35,183.74 ha (Fig. 2 and Table 3). However, if the missing mangrove patch of 3,741 ha is considered then the total mangrove cover should be *ca.* 38,924.74 ha. The ALOS data were efficient for mapping dominant mangrove species in the study area. Earlier, *Hamdan, Khali Aziz & Mohd Hasmadi (2014)* have used the ALOS data for identifying above ground biomass of the Matang Mangrove Forest Reserve (in Peninsular Malaysia) and found it advantageous to assess the vegetation across larger areas. The noise observed in the present supervised classification was chiefly associated with misclassification in-between *R. apiculata*, *S. caseolaris* and *N. fruticans* species. Differences in both *quantity* and *exchange* indicate that the area covered by *N. fruticans* was slightly underestimated due to *R. apiculata* and *S. caseolaris* interference in some locations (Figs. 6A–6B). Perhaps further

Table 4 Mangrove structural estimates. Mangrove tree structural estimates at Limbang, Sundar, Weston and Menumbok estuaries, Brunei Bay.
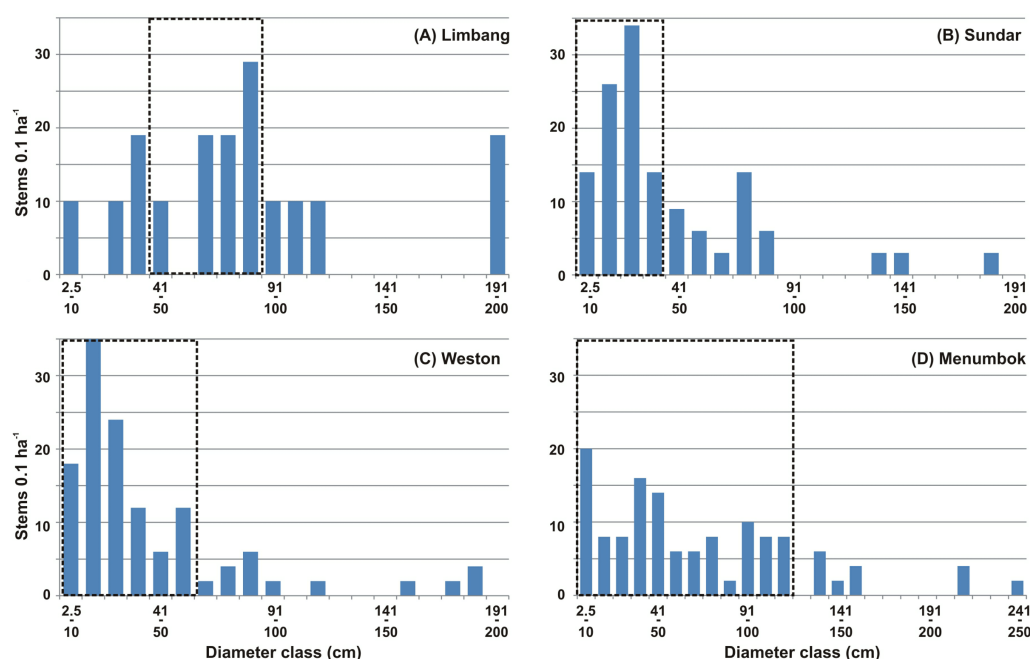
Estuary	Species	Density (trees 0.1 ha⁻¹)	Basal area (m² 0.1 ha⁻¹)	Relative density (%)	Relative dominance (%)	Relative frequency (%)	IV	Average tree height (m)	CI
Limbang	*Bruguiera gymnorrhiza*	10	0.07	5.9	0.1	10.0	16.0	6.0	844
	Nypa fruticans	38	20.40	23.5	17.0	30.0	70.5	6.8	
	Sonneratia caseolaris	77	51.41	47.1	42.8	40.0	129.9	11.7	
	Xylocarpus granatum	38	48.29	23.5	40.2	20.0	83.7	14.0	
	Total	**163**	**120.17**	**100**	**100**	**100**			
Sundar	*Avicennia alba*	6	0.29	4.3	0.9	6.5	11.7	11.0	303
	N. fruticans	23	14.73	17.0	44.3	16.1	77.4	6.7	
	Rhizophora apiculata	54	5.25	40.4	15.8	25.8	82.0	13.0	
	S. alba	20	7.90	14.9	23.8	19.4	58.1	13.1	
	S. caseolaris	11	0.54	8.5	1.6	12.9	23.0	9.0	
	X. granatum	20	4.53	14.9	13.6	19.4	47.9	12.3	
	Total	**134**	**33.24**	**100**	**100**	**100**			
Weston	*B. cylindrica*	8	0.20	6.1	0.6	9.7	16.4	11.4	239
	N. fruticans	31	25.91	24.2	73.8	29.0	127.0	7.7	
	R. apiculata	20	1.55	15.2	4.4	12.9	32.5	11.6	
	S. caseolaris	51	4.67	39.4	13.3	32.3	85.0	11.1	
	X. granatum	20	2.77	15.2	7.9	16.1	39.2	11.6	
	Total	**130**	**35.10**	**100**	**100**	**100**			
Menumbok	*Ceriops* sp.	2	0.01	1.5	0	2.9	4.4	9.0	519
	N. fruticans	42	50.01	31.8	61.6	28.6	122.0	7.9	
	R. apiculata	74	30.56	56.1	37.6	51.4	145.1	14.9	
	X. granatum	14	0.59	10.6	0.7	17.1	28.4	11.6	
	Total	**132**	**81.17**	**100**	**100**	**100**			

Notes.
IV, importance value; CI, complexity index.

understanding on the spectral reflectance properties of *Nypa*, *Rhizophora* and *Sonnertia* spp., would be able to improve the classification accuracy. In addition, application of the nonparametric algorithms like a Decision Tree could become advantageous for future mangrove mapping attempts (*Zhang et al., 2017*). The freely available moderate resolution satellite data (e.g., Sentinel) be a chance to correspond with the dates of ground inventory. On the other hand, pinpoint discrimination of the vegetation species, mixed with different age groups (juvenile, young and adult), is not practicable through the use of remote sensing data (*Xie, Sha & Yu, 2008*).

Mangrove species distribution at Brunei Bay (Fig. 2) coincides with the zonation patterns reported elsewhere. For example, succession by *Sonneratia* spp. at Limbang, Sundar and Weston river mouths indicates their pioneering nature along the open coasts on silty and silty-sand substrates (Fig. 6C) (*Satyanarayana et al., 2002*; *FAO, 2007*; *Satyanarayana et al., 2010*). However, *S. caseolaris* is also known to colonise the elevated (upstream) grounds (*Saenger, 2002*), and this could be a reason for its inland occurrence at Brunei

Figure 5 Mangrove diameter distribution. Mangrove diameter class distribution at (A) Limbang, (B) Sundar, (C) Weston and, (D) Menumbok estuaries. Dotted box in (A–D) shows the range of diameter contributed by more than 50% of the trees.

Full-size 🖼 DOI: 10.7717/peerj.4397/fig-5

Bay. According to *Nik Nurizni (2015)*, the varying surface water salinity between 7.2–19.3‰ and 0.6–21.3‰ at the downstream locations of Limbang (depth: 1.8 m) and Sundar (depth: 2.5 m) shows a considerable freshwater discharge in both areas (no water quality measurements are available for Weston). In contrast, the lower abundance of *Sonneratia* spp. at Menumbok river mouth as well as upstream areas could be linked to the lack of sediment accretion grounds (Fig. 2) and deep water channels (depth: 4.6 m and salinity: 22.8–27.9‰) (*Nik Nurizni, 2015*). The species like *Nypa fruticans* which inhabit soft and fine-grained substrates in the areas of strong freshwater discharge and *R. apiculata* in the areas of strong neritic incursion (cf. *Tomlinson, 1986*; *Saenger, 2002*; *Teh et al., 2008*; *Satyanarayana et al., 2010*) have shown their widespread distribution at Brunei Bay, whereas *X. granatum* is confined to the interior and elevated grounds (cf. *Satyanarayana et al., 2002*; *Satyanarayana et al., 2009*).

Tree structural parameters obtained from the mangroves are not only useful to identify the vegetation status, but also for monitoring/management through the silvicultural practices (*Dahdouh-Guebas & Koedam, 2006*). Among others, basal area represents wood volume and is beneficial to assess any vegetation in terms of its succession or maturation (*Satyanarayana et al., 2002*; *Satyanarayana et al., 2009*; *Satyanarayana et al., 2010*). At Brunei Bay, the higher basal area at Limbang and Menumbok shows the more matured nature of the trees as opposed to Sundar and Weston (Table 4). While the majority of trees with a diameter of 31–90 cm have contributed to the highest basal area at Limbang, the trees with

Figure 6 Fieldwork photographs. Photographic evidences showing (A) co-dominance of *Nypa fruticans* and *Rhizophora apiculata* at Sundar (signboard indicates the existence of crocodiles in this area), (B) co-dominance of *N. fruticans* and *Sonneratia caseolaris* at Weston, (C) succession of *S. caseolaris* at Limbang river mouth, (D) mangroves facing surplus inundation of the high tide at Sundar, (E) uprooted mangrove trees along the border facing bay waters, (F) dense *Rhizophora* vegetation at Menumbok (photos taken by Behara Satyanarayana).

Full-size 🖼 DOI: 10.7717/peerj.4397/fig-6

a 2.5–120 cm diameter were responsible for Menumbok. The diameter limited to 60 cm and less for a greater number of trees catered lower basal area for Sundar and Weston (Fig. 5). The complexity index, that depends largely on density, basal area and tree height estimates (*Holdridge et al., 1971*), could represent less/undisturbed nature of the vegetation along with

its potential contribution to the biodiversity at both Limbang and Menumbok (cf. (*Parkes, Newell & Cheal, 2003*; *Kovalenko, Thomaz & Warfe, 2012*; *Bartholomew, Hafezi & Karimi, 2016*; *Tongway & Ludwig, 2011*). The geographic location of Sundar and Weston, which is rather under the direct influence of bay waters, must be accountable for its less structural complexity. The mangroves here seemed to be experiencing a stressful environment due to surplus inundation, flood and ebb water current, etc., which in turn causing some trees to uproot (Figs. 6D–6E). It should be noticed that mangrove establishment and growth attains better along sheltered coastlines than to the open areas (*Alongi, 2008*).

The differences in terms of important mangrove species at each estuary between remote sensing and vegetation survey are understandable as the supervised classification provide details of the entire mangrove cover (Table 3), whereas the PCQM provide details of the two transect-based observations (Table 4). In fact, both ground-truth and remote sensing results were virtually complementing each other at the places of vegetation inventory (Fig. 2). However, we draw the attention to the preliminary nature of our study, emphasizing the need for longer transects and more sample points in multiple homogeneous mangrove patches (cf. *Engeman et al., 1994*; *Dahdouh-Guebas & Koedam, 2006*) to estimate the forest structural parameters with higher accuracy. In view of recent literature it might also be more interesting to measure the second or third nearest tree when applying PCQM (cf. *Hijbeek et al., 2013*; *Khan et al., 2016*).

The results of this study however had a limitation of comparison with other mangrove studies at Brunei Bay due to poor scientific literature. Also, our efforts to find the actual (Brunei Bay) mangrove area from Sabah and Sarawak Forestry Departments did not yield satisfactory results. Though Sabah Forestry Department has informed the mangrove cover at Weston and Menumbok as 14,932 ha (SA Sani, pers. comm., 2016), but this figure was different from the present observation i.e., 24,306.86 ha (20,565.86 ha [ALOS-based] + 3,741 ha [Google-based]). The main reason for this difference was due to 'state land' and 'forest land' categories of mangrove vegetation at Brunei Bay (Forestry Department do not consider the state land forest). Therefore, the present study (with dendrometric measurements and species-level mapping) is able to serve as a strong baseline data for future mangrove investigations at Brunei Bay, including for monitoring and management purposes locally at present.

CONCLUSIONS

Malaysian mangrove cover at Brunei Bay, from Limbang, Sundar, Weston and Menumbok estuaries, was evaluated for the first time by means of scientific measures invoking remote sensing (ALOS) and ground-truth (PCQM) data. Moderate resolution of the ALOS data was efficient for mapping dominant mangrove species in the vicinity. The spatial extent of the dominant mangroves was estimated at *ca.* 35,183.74 ha where *N. fruticans* occupied the highest land-cover followed by *R. apiculata*, *S. caseolaris*, *X. granatum* and *S. alba* in the order. Also, ground inventory revealed the abundance of *N. fruticans* and *R. apiculata* as widespread species while *S. caseolaris*, *X. granatum* and *S. alba* as locally distributed species at the river mouth and/or interior/elevated grounds. The other less

dominant species such as *A. alba*, *B. gymnorrhiza*, *B. cylindrica* and *Ceriops* sp. contributed insignificantly to the vegetation structure. High basal area at Limbang and Menumbok represents more matured nature of the vegetation as comparted to Sundar and Weston. Geographic location facing the direct influence of bay waters, surplus inundation, and flood and ebb water current were some of the issues believed to be responsible for low basal area and less mature vegetation at Sundar and Weston. Further understanding on the spectral reflectance properties of the co-dominant *Nypa*, *Rhizophora* and *Sonnertia* spp., along with application of the nonparametric algorithms like decision-tree, would be able to improve the accuracy of mangrove land-cover mapping. Overall, both remote sensing and ground-truth observations are in a general agreement to represent the (dominant) mangrove species composition and distribution at Brunei Bay and be able serve as a strong base-line data for future investigations.

ACKNOWLEDGEMENTS

ADDITIONAL INFORMATION AND DECLARATIONS

Funding

Grant Disclosures

Competing Interests

The authors declare there are no competing interests.

Author Contributions

- Behara Satyanarayana conceived and designed the experiments, performed the experiments, analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the paper, approved the final draft.
- Aidy M. Muslim analyzed the data, contributed reagents/materials/analysis tools, approved the final draft.
- Nurul Amira Izzaty Horsali and Nurul Ashikin Mat Zauki performed the experiments, analyzed the data, prepared figures and/or tables.

- Viviana Otero analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the paper, approved the final draft.
- Muhammad Izuan Nadzri prepared figures and/or tables.
- Sulong Ibrahim and Mohd-Lokman Husain conceived and designed the experiments, contributed reagents/materials/analysis tools, approved the final draft.
- Farid Dahdouh-Guebas authored or reviewed drafts of the paper, approved the final draft.

Field Study Permissions

The following information was supplied relating to field study approvals (i.e., approving body and any reference numbers):

This study was conducted with the permission of the State Forestry Department of Sarawak (# NCCD.907.4.4 (Jld. 10)-294).

Data Availability

The following information was supplied regarding data availability:

The raw data has been provided as Supplemental Files.

Supplemental Information

Supplemental information for this article can be found online at http://dx.doi.org/10.7717/peerj.4397#supplemental-information.

REFERENCES

Adiana G, Juahir H, Joseph B, Shazili NAM. 2017. Tracing the sources of lead (Pb) in Brunei Bay, Borneo by using integrated spectrometry ICP-MS and chemometric techniques. *Marine Pollution Bulletin* **123**:232–240 DOI 10.1016/j.marpolbul.2017.08.055.

Ahmad-Kamil EI, Ramli R, Jaaman SA, Bali J, Al-Obaidi JR. 2013. The effects of water parameters on monthly seagrass percentage cover in Lawas, East Malaysia. *The Scientific World Journal* **2013**:Article 892746 DOI 10.1155/2013/892746.

Ali I, Mohd. Ariff MR. 2007. The relationship of marine coastal ecosystem and river estuaries with the socioeconomic community of fishermen in Brunei Bay and Padas Bay, Sabah: a survey. *Jati* **12**:229–245.

Alkhadher SAA, Zakaria MP, Md Yusoff F, Kannan N, Suratman S, Keshavarzifard M, Magam SM, Masood N, Vaezzadeh V, Sani MSA. 2015. Baseline distribution and sources of linear alkyl benzenes (LABs) in surface sediments from Brunei Bay, Brunei. *Marine Pollution Bulletin* **101**:397–403 DOI 10.1016/j.marpolbul.2015.10.011.

Alongi DM. 2008. Mangrove forests: resilience, protection from tsunamis, and responses to global climate change. *Estuarine, Coastal and Shelf Science* **76**:1–13 DOI 10.1016/j.ecss.2007.08.024.

Aslan A, Rahman AF, Warren MW, Robeson SM. 2016. Mapping spatial distribution and biomass of coastal wetland vegetation in Indonesian Papua by combining active and passive remotely sensed data. *Remote Sensing of Environment* **183**:65–81 DOI 10.1016/j.rse.2016.04.026.

Bartholomew A, Hafezi SA, Karimi S. 2016. Effects of habitat complexity on the abundance, species richness and size of darkling beetles (Tenebrionidae) in artificial vegetation. *Journal of Arid Environments* **129**:35–41 DOI 10.1016/j.jaridenv.2016.02.004.

BirdLife International. 2015. Important bird and biodiversity areas (IBAs)—Brunei Bay (Malaysia). *Available at* http://www.birdlife.org (accessed on 14 May 2015).

Brunei Darussalam Forestry Department (FD). 2010. 4th National report to the convention on biological diversity, Brunei Darussalam. *Available at* https://www.cbd.int/reports/ (accessed on 26 May 2015).

Cárdenas NY, Joyce KE, Maier SW. 2017. Monitoring mangrove forests: are we taking full advantage of technology? *International Journal of Applied Earth Observation and Geoinformation* **63**:1–14 DOI 10.1016/j.jag.2017.07.004.

Castillo JAA, Apan AA, Maraseni TN, Salmo III SG. 2017. Estimation and mapping of above-ground biomass of mangrove forests and their replacement land uses in the Philippines using Sentinel imagery. *ISPRS Journal of Photogrammetry and Remote Sensing* **134**:70–85 DOI 10.1016/j.isprsjprs.2017.10.016.

Chauhan HB, Dwivedi RM. 2008. Inter sensor comparison between RESOURCESAT LISS III, LISS IV and AWiFS with reference to coastal landuse/landcover studies. *International Journal of Applied Earth Observation and Geoinformation* **10**:181–185 DOI 10.1016/j.jag.2007.10.007.

Chen B, Xiao X, Li X, Pan L, Doughty R, Ma J, Dong J, Qin Y, Zhao B, Wu Z, Sun R, Lan G, Xie G, Clinton N, Giri C. 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.

Cintrón G, Schaeffer Novelli Y. 1984. Methods for studying mangrove structure. In: Snedaker SC, Snedaker JG, eds. *The mangrove ecosystem: research methods.* Paris: UNESCO, 91–113.

Congalton RG. 1991. A review of assessing the accuracy of classifications of remotely sensed data. *Remote Sensing of Environment* **37**:35–46 DOI 10.1016/0034-4257(91)90048-B.

Cornforth WA, Fatoyinbo TE, Freemantle TP, Pettorelli N. 2013. Advanced land observing satellite phased array type L-Band SAR (ALOS PALSAR) to inform the conservation of mangroves: Sundarbans as a case study. *Remote Sensing* **5**:224–237 DOI 10.3390/rs5010224.

Cunningham AB. 2001. *Applied ethnobotany: people, wild plant use and conservation.* London: Earthscan Publications Limited.

Dahdouh-Guebas F, Koedam N. 2006. Empirical estimate of the reliability of the use of the Point-Centred Quarter Method (PCQM): solutions to ambiguous field situations and description of the PCQM+ protocol. *Forest Ecology and Management* **228**:1–18 DOI 10.1016/j.foreco.2005.10.076.

Dahdouh-Guebas F, Koedam N. 2008. Long-term retrospection on mangrove development using transdisciplinary approaches: a review. *Aquatic Botany* **89**:80–92 DOI 10.1016/j.aquabot.2008.03.012.

Dahdouh-Guebas F, Verheyden A, De Genst W, Hettiarachchi S, Koedam N. 2000.
Four decades vegetation dynamics in Sri Lankan mangroves as detected from
sequentialaerial photography: a case study in Galle. *Bulletin of Marine Science*
67:741–759.

De Santiago FF, Kovacs JM, Lafrance P. 2013. An object-oriented classification
method for mapping mangroves in Guinea, West Africa, using multipolarized
ALOS PALSAR L-band data. *International Journal of Remote Sensing* **34**:563–586
DOI 10.1080/01431161.2012.715773.

Duke NC. 2006. *Australia's mangroves.* Brisbane: University of Queensland.

Elzinga CL, Salzer DW, Willoughby JW, Gibbs JP. 2001. *Monitoring plant and animal
populations.* Massachusetts: Blackwell Science.

Engeman RM, Sugihara RT, Pank LF, Dusenberry WE. 1994. A comparison of
plotless density estimators using Monte Carlo simulation. *Ecology* **75**:1769–1779
DOI 10.2307/1939636.

Food and Agriculture Organization (FAO). 2007. *Mangrove guide book for South and
Southeast Asia (RAP/2006/07).* Bangkok: Dharmasarn Co., Ltd.

Giri C, Ochieng E, Tieszen LL, Zhu Z, Singh A, Loveland T, Masek J, Duke NC. 2011.
Status and distribution of mangrove forests of the world using earth observation
satellite data. *Global Ecology and Biogeography* **20**:154–159
DOI 10.1111/j.1466-8238.2010.00584.x.

Giri C, Pengra B, Zhu Z, Singh A, Tieszen L-L. 2007. Monitoring mangrove forest
dynamics of the Sundarbans in Bangladesh and India using multi-temporal
satellite data from 1973 to 2000. *Estuarine, Coastal and Shelf Science* **73**:91–100
DOI 10.1016/j.ecss.2006.12.019.

Giri C, Zhu Z, Tieszen LL, Singh A, Gillette S, Kelmelis JA. 2008. Mangrove forest
distributions and dynamics (1975–2005) of the tsunami-affected region of Asia.
Journal of Biogeography **35**:519–528 DOI 10.1111/j.1365-2699.2007.01806.x.

Hamdan O, Khali Aziz H, Mohd Hasmadi I. 2014. L-band ALOS PALSAR for biomass
estimation of Matang Mangroves, Malaysia. *Remote Sensing of Environment*
155:69–78 DOI 10.1016/j.rse.2014.04.029.

Hamdan O, Khali Aziz H, Shamsudin I, Raja Barizan RS. 2012. *Status of mangroves in
Peninsular Malaysia.* Kuala Lumpur: Forestry Department Peninsular Malaysia.

Hansen MC, Loveland TR. 2012. Remote sensing of environment: a review of large area
monitoring of land cover change using Landsat data. *Remote Sensing of Environment*
122:66–74 DOI 10.1016/j.rse.2011.08.024.

Hartoko A, Chayaningrum S, Febrianti DA, Ariyanto D, Suryanti. 2015. Carbon
biomass algorithms development for mangrove vegetation in Kemujan, Parang
Island Karimunjawa National Park and Demak coastal area–Indonesia. *Procedia
Environmental Sciences* **23**:39–47 DOI 10.1016/j.proenv.2015.01.007.

Hijbeek R, Koedam N, Khan MNI, Kairo JG, Schoukens J, Dahdouh-Guebas F. 2013.
An evaluation of plotless sampling using vegetation simulations and field data from a
mangrove forest. *PLOS ONE* **8**:e67201 DOI 10.1371/journal.pone.0067201.

Holdridge L, Grenke WC, Hatheway WH, Liang T, Tosi JA. 1971. *Forest environment in tropical life zones: a pilot study.* New York: Pergamon Press.

Jhonnerie R, Siregar VP, Nababan B, Prasetyo LB, Wouthuyzen S. 2015. Random forest classification for mangrove land cover mapping using Landsat 5 TM and ALOS PALSAR imageries. *Procedia Environmental Sciences* **24**:215–221 DOI 10.1016/j.proenv.2015.03.028.

Joseph J, Nishizawa H, Arshaad WM, Kadir SAS, Jaaman SA, Bali J, Jamaludin NA, Katoh M. 2016. Genetic stock compositions and natal origin of green turtle (*Chelonia mydas*) foraging at Brunei Bay. *Global Ecology and Conservation* **6**:16–24 DOI 10.1016/j.gecco.2016.01.003.

Joseph J, Nishizawa H, Hassan M, Zakariah MI, Jaaman SA, Xuelei Z. 2017. Utilization of Brunei Bay (Malaysia) as a developmental and foraging habitat for hawksbill turtle (*Eretmochelys imbricata*). *Regional Studies in Marine Science* **16**:304–307 DOI 10.1016/j.rsma.2017.09.012.

Justin SR. 2007. Surface and core sediment characteristics of mangrove in tidal dominated estuaries: Brunei Bay, Sabah. B.Sc. Thesis, University Malaysia Sabah.

Khan MNI, Hijbeek R, Berger U, Koedam N, Grueters U, Zahirul Islam SM, Md Asadul Hasan, Dahdouh-Guebas F. 2016. An evaluation of the plant density estimator the Point-Centred Quarter Method (PCQM) using Monte Carlo simulation. *PLOS ONE* **11**:e0157985 DOI 10.1371/journal.pone.0157985.

Khatami R, Mountrakis G, Stehman SV. 2016. A meta-analysis of remote sensing research on supervised pixel-based land-cover image classification processes: general guidelines for practitioners and future research. *Remote Sensing of Environment* **177**:89–100 DOI 10.1016/j.rse.2016.02.028.

Kovacs JM, Flores-Verdugo F, Wang J, Aspden LP. 2004. Estimating leaf area index of a degraded mangrove forest using high spatial resolution satellite data. *Aquatic Botany* **80**:13–22 DOI 10.1016/j.aquabot.2004.06.001.

Kovacs JM, Lu XX, Flores-Verdugo F, Zhang C, Flores de Santiago F, Jiao X. 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.

Kovacs JM, Wang J, Blanco-Correa M. 2001. Mapping disturbances in a mangrove forest using multi-date Landsat TM imagery. *Environmental Management* **27**:763–776 DOI 10.1007/s002670010186.

Kovalenko K, Thomaz S, Warfe D. 2012. Habitat complexity: approaches and future directions. *Hydrobiologia* **685**:1–17 DOI 10.1007/s10750-011-0974-z.

Kuenzer C, Bluemel A, Gebhardt S, Vo Quoc T, Dech S. 2011. Remote sensing of mangrove ecosystems: a review. *Remote Sensing* **3**:878–928 DOI 10.3390/rs3050878.

Leempoel K, Satyanarayana B, Bourgeois C, Zhang J, Chen M, Wang J, Bogaert J, Dahdouh-Guebas F. 2013. Dynamics in mangroves assessed by high-resolution and multi-temporal satellite data: a case study in Zhanjiang Mangrove National Nature Reserve (ZMNNR), P.R. China. *Biogeosciences* **10**:5681–5689 DOI 10.5194/bg-10-5681-2013.

Lucas R, Rebelo L-M, Fatoyinbo L, Rosenqvist A, Itoh T, Shimada M, Simard M, Souza-Filho PW, Thomas N, Trettin C, Accad A, Carreiras J, Hilarides L. 2014. Contribution of L-band SAR to systematic global mangrove monitoring. *Marine and Freshwater Research* **65**:589–603 DOI 10.1071/MF13177.

Mafi-Gholami D, Mahmoudi B, Zenner EK. 2017. An analysis of the relationship between drought events and mangrove changes along the northern coasts of the Persian Gulf and Oman Sea. *Estuarine, Coastal and Shelf Science* **199**:141–151 DOI 10.1016/j.ecss.2017.10.008.

Malaysian Ministry of Natural Resources and Environment (NRE). 2014. 5th National report to the convention on biological diversity, Malaysia. *Available at https://www.cbd.int/reports/* (accessed on 27 May 2015).

Malik AQ. 2011. Assessment of the potential of renewables for Brunei Darussalam. *Renewable and Sustainable Energy Reviews* **15**:427–437 DOI 10.1016/j.rser.2010.08.014.

Massó i Alemán S, Bourgeois C, Appeltans W, Vanhoorne B, De Hauwere N, Stoffelen P, Heaghebaert A, Dahdouh-Guebas F. 2010. The mangrove reference database and herbarium. *Plant Ecoloy and Evolution* **143**:225–232 DOI 10.5091/plecevo.2010.439.

Natural Resources Canada (NRC). 2006. Fundamentals of remote sensing: a Canada Centre for Mapping and Earth Observation tutorial. *Available at http://www.nrcan.gc.ca/earth-sciences/geography-boundary/remote-sensing/fundamentals/1430* (accessed on 1 August 2014).

Nelson BR, Satyanarayana B, Zhong JMH, Shaharom F, Sukumaran M, Chatterji A. 2015. Episodic human activities and seasonal impacts on the *Tachypleus gigas* (Müller, 1795) population at Tanjung Selangor in Peninsular Malaysia. *Estuarine, Coastal and Shelf Science* **164**:313–323 DOI 10.1016/j.ecss.2015.08.003.

Neukermans G, Dahdouh-Guebas F, Kairo JG, Koedam N. 2008. Mangrove species and stand mapping in Gazi Bay (Kenya) using QuickBird satellite imagery. *Journal of Spatial Science* **53**:75–86 DOI 10.1080/14498596.2008.9635137.

Nguyen HH, McAlpine C, Pullar D, Johansen K, Duke NC. 2013. The relationship of spatial–temporal changes in fringe mangrove extent and adjacent land-use: case study of Kien Giang coast, Vietnam. *Ocean & Coastal Management* **76**:12–22 DOI 10.1016/j.ocecoaman.2013.01.003.

Nik Nurizni NA. 2015. Water quality in relation to flood and ebb tide conditions inside the mangrove channels at Brunei Bay. B.Sc. Thesis, Universiti Malaysia Terengganu.

Parkes D, Newell G, Cheal D. 2003. Assessing the quality of native vegetation: the 'habitat hectares' approach. *Ecological Management & Restoration* **4**:S29–S38 DOI 10.1046/j.1442-8903.4.s.4.x.

Pontius Jr RG, Millones M. 2011. Death to Kappa: birth of quantity disagreement and allocation disagreement for accuracy assessment. *International Journal of Remote Sensing* **32**:4407–4429 DOI 10.1080/01431161.2011.552923.

Pontius Jr RG, Santacruz A. 2014. Quantity, exchange, and shift components of difference in a square contingency table. *International Journal of Remote Sensing* **35**:7543–7554 DOI 10.1080/2150704X.2014.969814.

Proisy C, Féret J-B, Lauret N, Gastellu-Etchegorry J-P. 2016. Mangrove forest dynamics using very high spatial resolution optical remote sensing. In: *Land surface remote sensing in urban and coastal areas.* London and Amsterdam: ISTE Press—Elsevier Press, 269–295.

Proum S, Santos JH, Lim LH, Marshall DJ. 2016. Metal accumulation in the tissues and shells of *Indothais gradata* snails inhabiting soft and hard substrata in an acidified tropical estuary (Brunei, South East Asia). *Regional Studies in Marine Science* **8**:487–497 DOI 10.1016/j.rsma.2016.03.010.

Saenger P. 2002. *Mangrove ecology, silviculture and conservation.* London: Kluwer Academic Publishers.

Satyanarayana B, Idris IF, Mohamad KA, Mohd-Lokman H, Shazili NAM, Dahdouh-Guebas F. 2010. Mangrove species distribution and abundance in relation to local environmental settings: a case-study at Tumpat, Kelantan Delta, east coast of peninsular Malaysia. *Botanica Marina* **53**:79–88 DOI 10.1515/BOT.2010.006.

Satyanarayana B, Mohamad KA, Idris IF, Mohd-Lokman H, Dahdouh-Guebas F. 2011. Assessment of mangrove vegetation based on remote sensing and ground-truth measurements at Tumpat, Kelantan Delta, East Coast of Peninsular Malaysia. *International Journal of Remote Sensing* **32**:1635–1650 DOI 10.1080/01431160903586781.

Satyanarayana B, Raman AV, Dehairs F, Kalavati C, Chandramohan P. 2002. Mangrove floristic and zonation patterns of Coringa, Kakinada Bay, East Coast of India. *Wetlands Ecology and Management* **10**:25–39 DOI 10.1023/A:1014345403103.

Satyanarayana B, Raman AV, Mohd-Lokman H, Dehairs F, Sharma VS, Dahdouh-Guebas F. 2009. Multivariate methods distinguishing mangrove community structure of Coringa in the Godavari Delta, East coast of India. *Aquatic Ecosystem Health & Management* **12**:401–408 DOI 10.1080/14634980903334074.

Seto KC, Fragkias M. 2007. Mangrove conversion and aquaculture development in Vietnam: a remote sensing-based approach for evaluating the Ramsar Convention on Wetlands. *Global Environmental Change* **17**:486–500 DOI 10.1016/j.gloenvcha.2007.03.001.

Shafri HZM, Suhaili A, Mansor IS. 2007. The performance of maximum likelihood, spectral angle mapper, neural network and decision tree classifiers in hyperspectral image analysis. *Journal of Computer Science* **3**:419–423 DOI 10.3844/jcssp.2007.419.423.

Spalding M, Kainuma M, Collins L. 2010. *World Atlas of Mangroves.* London: Earthscan Publications Limited.

Sulong I, Mohd-Lokman H, Mohd-Tarmizi K, Ismail A. 2002. Mangrove mapping using LANDSAT imagery and aerial photographs: Kemaman District, Terengganu, Malaysia. *Environment, Development and Sustainability* **4**:135–152 DOI 10.1023/A:1020844620215.

Teh SY, DeAngelis DL, Sternberg LSL, Miralles-Wilhem FR, Smith III TJ, Koh H-L. 2008. A simulation model for projecting changes in salinity concentrations and species dominance in the coastal margin habitats of the Everglades. *Ecological Modelling* **213**:245–256 DOI 10.1016/j.ecolmodel.2007.12.007.

Tian J, Wang L, Li X, Gong H, Shi C, Zhong R. 2017. Comparison of UAV and WorldView-2 imagery for mapping leaf area index of mangrove forest. *International Journal of Applied Earth Observation and Geoinformatics* **61**:22–31 DOI 10.1016/j.jag.2017.05.002.

Tomlinson PB. 1986. *The Botany of Mangroves.* New York: Cambridge University Press.

Tongway DJ, Ludwig JA. 2011. Vegetation assessments: structure and habitat complexity indicators. In: *Restoring disturbed landscapes; putting principles into practice.* Washington, D.C.: Island Press, 157–162.

Vo ST, Pernetta JC, Paterson CJ. 2013. Status and trends in coastal habitats of the South China Sea. *Ocean & Coastal Management* **85**:153–163 DOI 10.1016/j.ocecoaman.2013.02.018.

Walcker R, Gratiot N, Anthony EJ. 2016. Remote sensing-based monitoring of the muddy mangrove coastline of French Guiana. In: *Land surface remote sensing in urban and coastal areas.* London and Amsterdam: ISTE Press—Elsevier Press, 297–320.

Walters BB, Rönnbäck P, Kovacs JM, Crona B, Hussain SA, Badola R, Primavera JH, Barbier E, Dahdouh-Guebas F. 2008. Ethnobiology, socio-economics and management of mangrove forests: a review. *Aquatic Botany* **89**:220–236 DOI 10.1016/j.aquabot.2008.02.009.

Wang L, Sousa WP, Gong P. 2004. Integration of object-based and pixel-based classification for mapping mangroves with IKONOS imagery. *International Journal of Remote Sensing* **23**:5655–5668 DOI 10.1080/014311602331291215.

Wang L, Sousa WP, Gong P, Biging GS. 2004. Comparison of IKONOS and QuickBird images for mapping mangrove species on the Caribbean coast of Panama. *Remote Sensing of Environment* **91**:432–440 DOI 10.1016/j.rse.2004.04.005.

WU (Weather Underground). 2015. Weather History for Labuan, Malaysia. Certified by National Oceanic and Atmospheric Administration (NOAA). *Available at http://www.wunderground.com/history.html* (accessed on 25 May 2015).

Xie Y, Sha Z, Yu M. 2008. Remote sensing imagery in vegetation mapping: a review. *Journal of Plant Ecology* **1**:9–23 DOI 10.1093/jpe/rtm005.

Zhang X, Treitz PM, Chen D, Quan C, Shi L, Li X. 2017. Mapping mangrove forests using multi-tidal remotely-sensed data and a decision-tree-based procedure. *International Journal of Applied Earth Observation and Geoinformation* **62**:201–214 DOI 10.1016/j.jag.2017.06.010.