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A Late Holocene Record of Coastal Wetland Development and Fire Regimes in Tropical Northern Australia

Lydia Mackenzie[1, 2*], Patrick Moss[2, 3], Sean Ulm[4]

[1] Department of Geography, School of Earth Sciences, Zhejiang University, Hangzhou 310027, China

[2] School of Earth and Environmental Sciences, The University of Queensland, Australia, lydia_mackenzie@zju.edu.cn

[3] ARC Centre of Excellence for Australian Biodiversity and Heritage, The Australian National University, Canberra, ACT, 2601, Australia

[4] ARC Centre of Excellence for Australian Biodiversity and Heritage, College of Arts, Society and Education, James Cook University, PO Box 6811, Cairns, QLD 4870, Australia

Abstract

This study presents three records of environmental change during the late Holocene from wetlands across Bentinck Island in the South Wellesley Islands, northern Australia. Radiometric dating was used to provide an age for sediment cores with the longest chronology spanning the last 1,250 cal. yr BP. Palynological results show the diverse mangrove community transitioned to woodland- and wetland-dominated vegetation over the last 850 years on the southeast coast. The key driver of this landscape change was likely late Holocene sea level regression and coastal progradation in the Gulf of Carpentaria. This study found freshwater wetlands expanded across Bentick Island over the last 500 years, with sedges and rushes peaking in the last 350 years. Macroscopic and microscopic charcoal records, coupled with archaeological evidence, highlights the spatial and temporal variation in fire regimes across the island, reflecting the traditional fire management practices of the Kaiadilt people during the late Holocene. This study finds a significant increase in charcoal accumulation in the 1900s, when Kaiadilt fire practices were disrupted and the South Wellesley Islands were abandoned. The pollen record reflects little change in the vegetation despite the shifting fire regime, highlighting the importance of multi-proxy approaches to reconstructing past environments in tropical northern Australia where vegetation is adapted to fire.

Keywords

Palynology; charcoal; fire; vegetation change; coastal; island; northern Australia

Introduction

Palaeoenvironmental records from the coastal lowlands of tropical northern Australia document significant vegetation change during the Holocene (Woodroffe et al., 1985; Chappell, 1988; Proske, 2016). The limited number of palaeoenvironmental reconstructions from northern Australia suggest that there are several drivers of vegetation change during the Holocene including variable sea-level, climate and fire regimes. Sea-level rise in the early Holocene, followed by a high-stand in the mid-Holocene, inundated coastal regions of northern Australia and allowed mangrove communities to expand during a 'big swamp' phase (Woodroffe et al., 1985). Hypersaline mudflats expanded in low-lying regions in the mid-to-late Holocene as mangrove communities contracted due to sediment accretion, falling sea levels and prograding shorelines (Woodroffe and Grindrod, 1991; Woodroffe, 1993; Reeves et al., 2013; Proske, 2016; Woodroffe, 2000). The prograding shoreline formed coastal swales and redirected palaeochannels, causing mangroves and saline mudflat areas to transition to freshwater wetlands during the late Holocene, with wetland development dependent on local geomorphic processes (Chappell, 1988; Woodroffe, 1988; Proske et al., 2014; Barham, 1999; Rowe, 2006; Rowe, 2015; Crowley and Gagan, 1995; Moss et al., 2015).

Climate also played a role in vegetation development and wetland expansion during the Holocene. Records across tropical northern Australia identify a drying trend and increasing climatic variability (Donders et al., 2007; Field et al., 2017; Reeves et al., 2013) as the strength and intensity of El Niño-Southern Oscillation (ENSO) increased in the last 5,000 years (Gagan et al., 2004; Moy et al., 2002; Prebble et al., 2005) and the summer monsoon decreased in strength causing a peak in aridity from 1,500-1,200 cal. yr BP (calendar years Before Present) (Denniston et al., 2013). The summer monsoon strengthened from 1,200 cal. yr BP (Denniston et al., 2013), coinciding with several freshwater wetlands developing or expanding in the last 1,000 years (Shulmeister, 1992; Stephens and Head, 1995; Rowe, 2015; McGowan et al., 2012; Stevenson et al., 2015; Proske, 2016; Denniston et al., 2013; Field et al., 2017). Increased effective precipitation during the late Holocene caused wetland taxa including Restionaceae, Cyperaceae and *Myriophyllum*, to increase in palynological records from tropical northern Australia (Shulmeister, 1992; Prebble et al., 2005; Rowe, 2015).

Fire significantly affects vegetation composition and distribution in northern Australia (e.g. Bowman et al., 2010). Fire activity increased during the Holocene in northern Australia, complicating the relationship between fire, climate and vegetation (see Shulmeister, 1992; Prebble et al., 2005; Rowe, 2015). The regional climate promotes frequent bushfires due to the dominant dry-season south-easterly winds, low humidity and high temperatures (Gill et al., 1996). In the current environment the majority of fires are anthropogenic with lightning strikes igniting a small proportion during the transition from the dry to wet season (Bowman et al., 1988; Yibarbuk et al., 2001). Human populations expanded across tropical northern Australia in the late Holocene and the exploitation of coastal resources increased (Williams et al., 2015a; Ulm, 2011). Shell-mound building peaked between ~4,000 and 500 years ago as prograding shorelines increased intertidal shellfish resources (Brockwell et al., 2009) and islands including the Wellesley and the Sir Edward Pellew groups in the Gulf of Carpentaria were resettled (Sim and Wallis, 2008; Rosendahl et al., 2015).

This study examines vegetation community response to environmental change during the Holocene in tropical northern Australia. Palynological analysis of sediments from three wetlands on Bentinck Island provide new records of vegetation and wetland expansion during the late Holocene, building on the pilot study by Moss et al. (2015) which produced a 2,400 year record of vegetation change and fire. Uncertainty in the pilot study's age-depth model is improved in this study by incorporating lead-210 and radiocarbon dates for each of the sites. The spatial resolution is also improved by examining multiple sites across Bentinck Island in the South Wellesley Islands, building a regional record of wetland development, fire regimes and vegetation change during the late Holocene. Microscopic (particles <185µm) and continuous macroscopic (particles >125µm) charcoal analysis provides the basis for reconstructing regional and local fire regimes, identifying periods of human activity and island abandonment, independent from the palynological records. This study investigates the impact of anthropogenic and climate-driven environmental change by comparing records of vegetation, fire and sea-level change with the archaeological evidence of human occupation on Bentinck Island.

Study Site

Bentinck Island (144 km^2) is the largest of the South Wellesley Islands and is situated 26 km off the coast in the southern Gulf of Carpentaria, northern Australia (Figure 1; 17˚04'S, 139˚29' E). The island's lateritic outcrops form cliffs up to 5m high along exposed coastlines and inland mudflats, with extensive Holocene sand dunes reaching 22m above mean sea level along the northeast coast (Grimes, 1979).

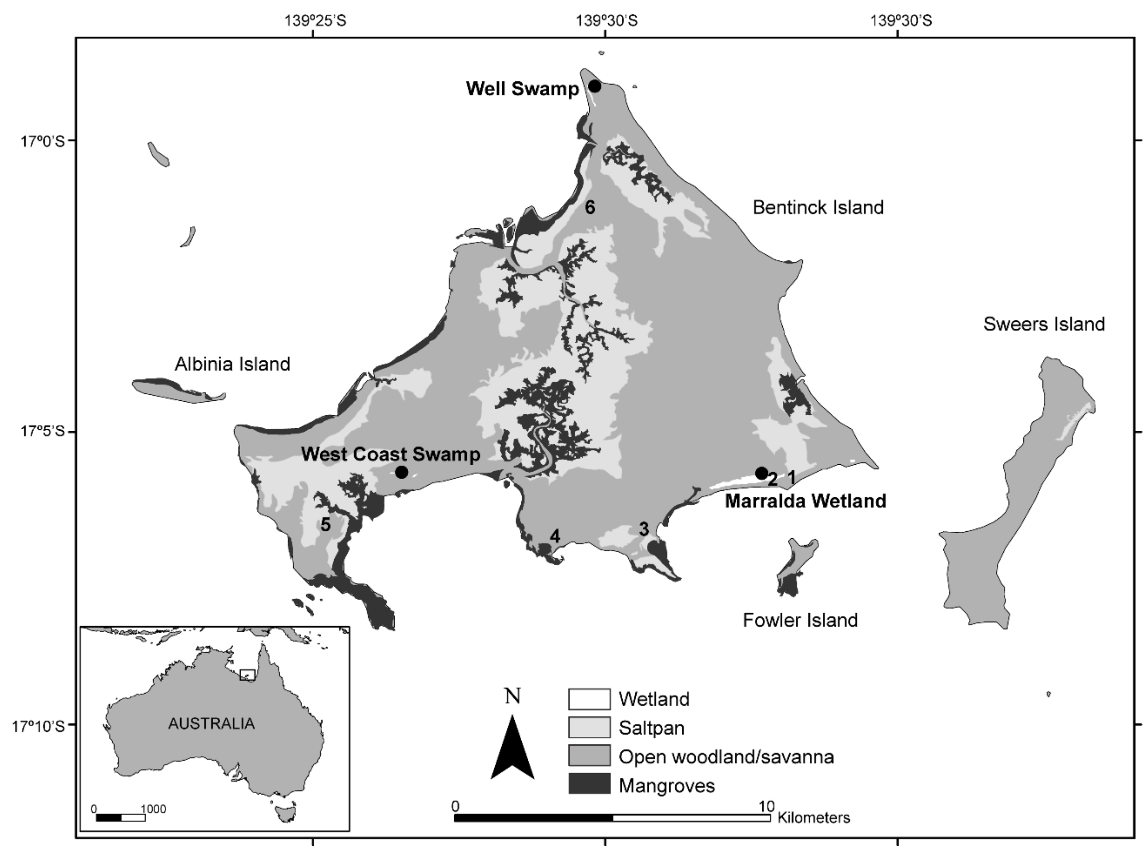

Figure 1. Map of the South Wellesley Islands, with sites of cores for palaeoenvironmental reconstructions (circles) and archaeological excavations (numbers) discussed in text. 1. Jirrkamirndiyarrb, 2. Murdumurdu, 3. Banbanbarukeind, 4. Wirringaji, 5. Dangkankururwuru, 6. Thundiy.

The climate is seasonally variable and the prevailing winds and rainfall are driven by the Australian Monsoonal system (Nix, 1983; Suppiah, 1992; Sturman and Tapper, 1996). South-easterly winds dominate during the longer dry season from April to October. During the shorter wet season (November-March), the region receives ~90% of its annual rainfall and winds are light and variable, predominantly from the northwest. The region receives an average of 1200 mm of rainfall per annum with an average monthly temperature maximum of 33˚C and minimum of 16˚C (Bureau of Meteorology, 2016).

The Wellesley Islands vegetation is atypical northern Australian tropical savanna or open woodland (Stern et al., 2000). Vegetation surveys by Thomas and Pedley (2005), Rosendahl (2012) and the author (Mackenzie, 2016) describe the vegetation of Bentinck Island. The island is divided by a mudflat dominated by Amaranthaceae, with ephemeral streams draining seasonal rainfall towards the coast. Mangrove communities, dominated by *Rhizophora stylosa, Ceriops tagal* and *Bruguiera exaristata*,occupy mudflats and shorelines. The landward edge of mangroves and coastal dunes also support *Melaleuca acacioides* and open grasslands dominated by *Spinifex* spp. *Pandanus spiralis* grows in poorly drained areas within eucalyptus communities, around wetlands and in dune swales. *Eucalyptus*, *Corymbia* and *Acacia* spp. form the dominant tropical savanna communities on back dunes and the nutrient-poor soils of the island's interior. *Melaleuca* spp. characterise the vegetation community in poorly drained freshwater areas and species of Cyperaceae and Typhaceae are common. Monsoon vine thicket communities are found in small patches across a range of soil types, however distribution is restricted primarily by fire regimes, rather than edaphic controls (Shulmeister, 1994; Russell-Smith, 1986; Stocker, 1966). Fire sensitive species are restricted to protected sites in the South Wellesley Islands, such as in the fire-shadow of dunes and ridges sheltered from the prevailing dry season south-easterly winds. Canopy tree species include *Diospyros humilis, Celtis* spp., *Canarium australianum* and *Mallotus nesophilus*.

There are abundant Kaiadilt occupation sites across the South Wellesley Islands, often associated with the coastal wetlands, with the majority of archaeological material dated to the last 300 years suggesting intensified occupation (Ulm et al., 2010; Memmott et al., 2016; Slater 2019). Marralda Wetland (MARR04; S 17.09631, E 139.54265; 3m above modern sea level) runs parallel to the coastline, occupying swales that developed as the shoreline prograded in the late Holocene, on the southeast coast of Bentinck Island (Moss et al., 2015; Mackenzie et al., 2016). Coastal dunes adjacent to the Marralda Wetland support abundant shell middens with archaeological excavations at the nearby Jirrkamirndiyarrb (1.2 km to the east of Marralda Wetland, **Error! Reference source not found.**, number 1) suggesting people visited the area as early as 3,500 cal. yr BP (Ulm et al., 2010; Peck 2016). Murdumurdu (Figure 1, number 2) is situated on a foredune roughly 500 m west of Marralda Wetland and records a short period of intense occupation around 300 cal. yr BP (Twaddle et al., 2017). West Coast Swamp (WCS01; S 17.0948, E 139.43964; 5 m above modern sea level) is located behind a series of dunes. The immediate region around West Coast Swamp lacks the large cultural deposits found at other sites and the vegetation shows no evidence of recent fires. However, surface archaeological deposits are found within 1km of the site (Ulm pers. com) and Dangkankuruwuru (Figure 1, number 5) is roughly 3km to the southwest. The Dangkankuruwuru excavation records intense occupation from 1250 to 1000 cal. yr BP and 250 cal. yr BP to present (Peck, 2016). Well Swamp (WS01; S 16.9846, E 139.49504; 2m above modern sea level) is an ephemeral wetland located on the northeast coast of Bentinck Island. Archaeological evidence records local activity at Thundiy (Figure 1, number 6) which is a relatively deep and high-density shell midden around 3km to the south of Well Swamp. The site records 800 years of human occupation with intensive occupation in the last 250 years (Peck, 2016; Moss et al., 2019; Nagel et al., 2016).

Methodology

Cores were collected in July 2012/2013 using a D-section hand corer. Cores were described in the field and subsampled in the laboratory.

Chronology

Six subsamples from each core were analysed for lead-210 (^{210}Pb) at the Australian Nuclear Science and Technology Organisation (ANSTO), in order to identify the sedimentation rates for the last 120 years (see Moss et al., 2015). The ^{210}Pb dates were produced using the constant initial concentration (CIC) model (Goldberg et al., 1977; Robbins and Edgington, 1975). Five bulk sediment samples were AMS radiocarbon dated (^{14}C) at ANSTO and calibrated using the ShCal13 curve (Hogg et al., 2013). Basal dates of cores and age-depth models are reported in Mackenzie et al., (2016) as 1114, 538 and 461 cal. yr BP for MARR04, WCS01 and WS01 respectively. Age-depth models for each site combined the ^{210}Pb with the AMS ^{14}C dates using the CLAM package for the R studio software (Blaauw, 2010; RStudio Team, 2015).

Pollen and Charcoal Analysis

Cores were subsampled for pollen and microscopic charcoal analysis depending on the sedimentation rate. One cm^3 subsamples from the MARR04 core was taken every 4cm between 0-20cm owing to poor pollen preservation? and every 2cm between 20-50cm. The WS01 core was sampled every 2cm and the WCS01 record at every 2cm between 0-30cm, then every 4cm due to poor pollen preservation in the lower deposit. Sample preparation for pollen and microscopic charcoal followed the technique of Moss (2013). Samples were disaggregated in 10% tetra-sodium pyrophosphate ($Na_4P_2O_7.10H_2O$) before adding a *Lycopodium* marker tablet to samples to determine the relative concentrations of microscopic charcoal and pollen. Sieving through a 185 μm mesh and 8 μm nylon mesh removed organic and inorganic particles outside the range of pollen grains. Heavy-liquid flotation ($3Na_2WO_4.9WO_3.H_2O$) with a specific gravity of 1.9 separated the organic fraction from inorganic sediments, before treating the remaining pollen fraction with acetolysis. Pollen grains were counted using a light microscope at 400x magnification, with pollen identification aided by the Australian Pollen and Spore Atlas (http://apsa.anu.edu.au/) and the extensive work on mangrove pollen by Thanikaimoni (1987) and Mao et al. (2012). 200 grains were identified per sample in MARR04. In the other two cores pollen concentrations were lower with a minimum of 100 grains counted per sample or, in layers with high clay and low organic content (see: Mackenzie et al., 2016), two full slides were counted. The pollen sum of all taxa were displayed using TG View (2004; Grimm, 1987). Constrained incremental sums of squares (CONISS) cluster analysis was used to statistically determine zonation (Grimm, 1987, 2004). Microscopic charcoal (black, opaque, angular particles >10μm) was counted at 400x magnification across three randomly selected transects on slides prepared for pollen. Small particles travel long distances, and represent regional fire (Whitlock and Larsen, 2001; Mooney and Tinner, 2010; cf. Woodward and Haines in press). Lycopodium spores were counted simultaneously and charcoal data converted to concentrations ($x10^3$ particles/cm^3).

Subsamples (1cm^3) were taken at 1cm increments for macroscopic charcoal analysis (>125µm) following the methodology of Mooney and Tinner (2010). Samples were dispersed using a 10% sodium pyrophosphate solution, bleached overnight in a 6% HCL solution and then passed through a 125µm sieve. Charcoal was counted using a Leica stereo microscope, with raw data combined with age-depth models and analyzed using CharAnalysis (Higuera et al., 2009). Peaks in the charcoal accumulation rate (pieces cm^{-2} yr^{-1}) identify local fires (0.5-1km) (Higuera et al., 2008).

Results

Stratigraphy and Chronology

The basal unit of Marralda Wetland was a fine-to-medium-grained brown/grey muddy sand, with large amounts of shell hash and pisoliths present. This unit graded into a dark brown, sandy mud around 42cm as both clay and sand decreased, with organic content increasing towards the top of the core (22-0cm). The WCS01 core consisted of a medium, poorly sorted silt with mottling present in the greyish brown basal sediment. There was a transition to a brown/grey silt from 35cm to the top of the core. The top 2cm contained more organic material and was a brown/grey. The basal unit of the WS01 core was a coarse, poorly sorted silt, light grey in colour which transitioned to a brown/grey silt at 15 cm depth and brown/black silt with high organic content in the top 7cm.

A smooth spline interpolation built continuous age-depth models for each core, incorporating the CIC modelled ^{210}Pb and calibrated ^{14}C dates (Mackenzie et al., 2016). Chronologies show all cores are of late Holocene age, with sedimentation rates increasing at MARR04 and WCS01 in the last 50 and 100 years, respectively.

Pollen and Charcoal Analysis

The pollen assemblages of the cores are shown in Figures 2-4, with a summary and pollen diagram for each site. Summary diagrams include a high resolution and x-radiograph image of the sediment cores taken with the ITRAX XRF (X-Ray Fluorescence) core scanner at ANSTO. The pollen distribution (%) is divided into sclerophyll taxa, Amaranthaceae, herbs, grasses and vines, freshwater aquatic taxa and mangroves. The summary diagram shows the pollen concentration (grains/cm^3), raw macroscopic charcoal counts (particles/cm^3) and microscopic charcoal concentration (particles/cm^3) for each site. Zones defined by CONISS are included in the summary diagrams. Charcoal accumulation rates (particles cm^{-3} yr^{-1}) for both microscopic and macroscopic charcoal are presented in Figure 5.

Full pollen diagrams are plotted against age, with taxa separated into monsoon vine thicket, sclerophyll taxa, herbs, grasses and vines, freshwater aquatics and mangroves. Pollen which contribute less than 1% of the pollen sum are included as ‘present’ (black circle).

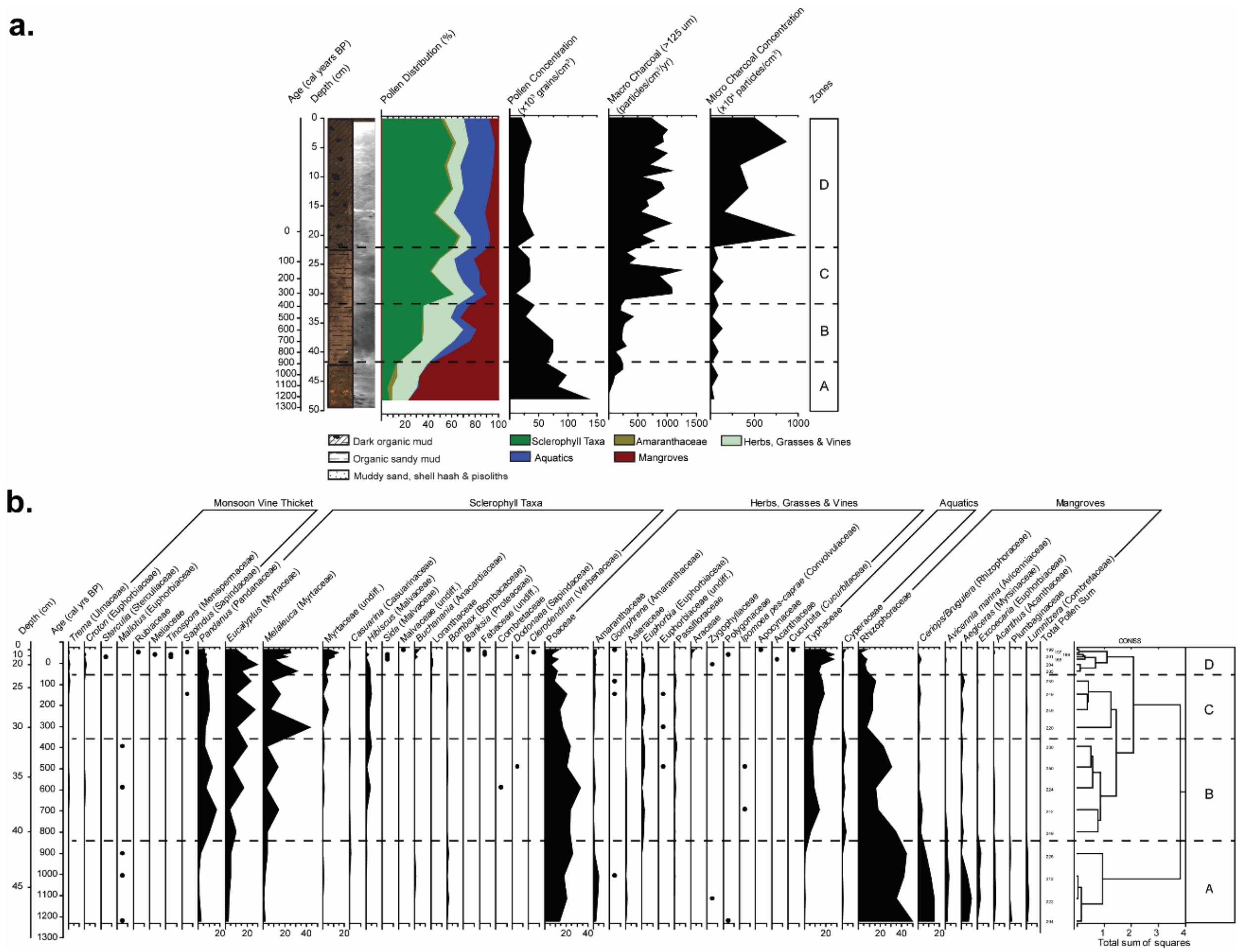

Figure 2. Marralda Wetland (MARR04) pollen and charcoal results including (a) Summary diagram including high resolution imaging, sedimentary characteristics, pollen distribution and concentration, microscopic and raw macroscopic charcoal results. (b) Full pollen diagram plotted against age, including monsoon vine thicket, sclerophyll taxa, herbs, grasses & vines, freshwater aquatic taxa and mangroves. CONISS defines zonations.

Core MARR04

MARR04-A: 50-42.5cm depth, ca. 1250-850 cal. yr BP

Zone A of MARR04 is characterised by abundant mangrove types (>65%) including *Rhizophora* spp. (40-50%), *Ceriops/Bruguiera* spp (2.5-15%), *Aegiceras corniculatum* (approx. 10%), *Acanthus* spp. (approx. 2%), *Avicennia marina, Excoecaria* spp., *Plumbaginaceae* spp. and *Lumnitzera* spp. (all <4%). Poaceae (14-18%) and *Eucalyptus* (3-5%) were present, along with Amaranthaceae (2-5%), which reached its highest abundance in Zone A. *Pandanus* and *Melaleuca* (< 2%) and the monsoon vine thicket taxa *Mallotus* (<1%) was also present. Low microscopic and macroscopic charcoal accumulation occurred in this zone.

MARR04-B: 42.5-32cm depth, ca. 850-350 cal. yr BP

Zone B was dominated by open woodland and savanna vegetation as Poaceae (23-33%) reached its highest value. *Eucalyptus* (10-20%), *Melaleuca* (1.5-14.5%) and *Pandanus* (6-10%) increased. *Rhizophora* (16-35%) values remained high, as other mangrove taxa declined including *Avicennia, Ceriops/Bruguiera, Aegiceras* and *Acanthus* (≤ 2%). Minor taxa included *Hibiscus* (4%), Amaranthaceae, (≤ 2%) and the monsoon vine thicket type *Trema* (<1%). Freshwater aquatic taxa Cyperaceae (2-4%) and Typha (6-9%) appeared for the first time in Zone B. Charcoal accumulation rates are similar to Zone A and the pollen concentration declined towards the top.

MARR04-C: 32-22cm depth, ca. 350 cal. BP-AD 1900

Zone C was characterised by increasing values of open woodland taxa, including *Eucalyptus* (20-29%), and Myrtaceae (undif.) (5%). *Melaleuca* (6-18%), *Pandanus* (7-10%) and *Hibiscus* (≤ 4%) were also present. *Rhizophora* (7-16%) pollen declined with other taxa including *A. marina*, *Aegiceras* spp and *Acanthus* spp (all ≤ 3%). Poaceae (6-14%) declined and the diversity of herbs increased, including Acanthaceae, Asteraceae (Tubulifloreae), Amaranthaceae, Passifloraceae and *Gomphrena* (all ≤ 3%). Monsoonal vine thicket taxa were present including Ulmaceae and *Croton* (1%). The aquatic taxon *Typha* (13-27%) increased towards the top of Zone C with Cyperaceae (1%) at minimal values. Macroscopic charcoal accumulation increased significantly between 300-100 cal. yr BP. Microscopic charcoal accumulation remained low and the pollen concentration declined to its lowest values in the core (10 x 10^3 grains/cm^3).

MARR04-D: 22-0cm depth, AD 1900– present

The uppermost zone was dominated by open woodland and savanna vegetation (60.5-76% combined). *Eucalyptus* (11-19%) and Myrtaceae (undif.) (6-14%) declined towards the top, replaced by *Melaleuca* (16-25%). Poaceae (6-13%) values were low while Amaranthaceae (≤ 3%) remained relatively stable. A range of monsoon vine thicket taxa and associates were present including *Trema, Croton, Sterculia,* Rubiaceae, *Meliaceae, Tinospora* and Sapindaceae (all ≤ 1%). Mangrove taxa (2.5-11%) were present and *Typha* (19-27%) peaked in Zone D. Pollen concentrations remained relatively low while microscopic and macroscopic charcoal influx increased significantly after AD 1900.

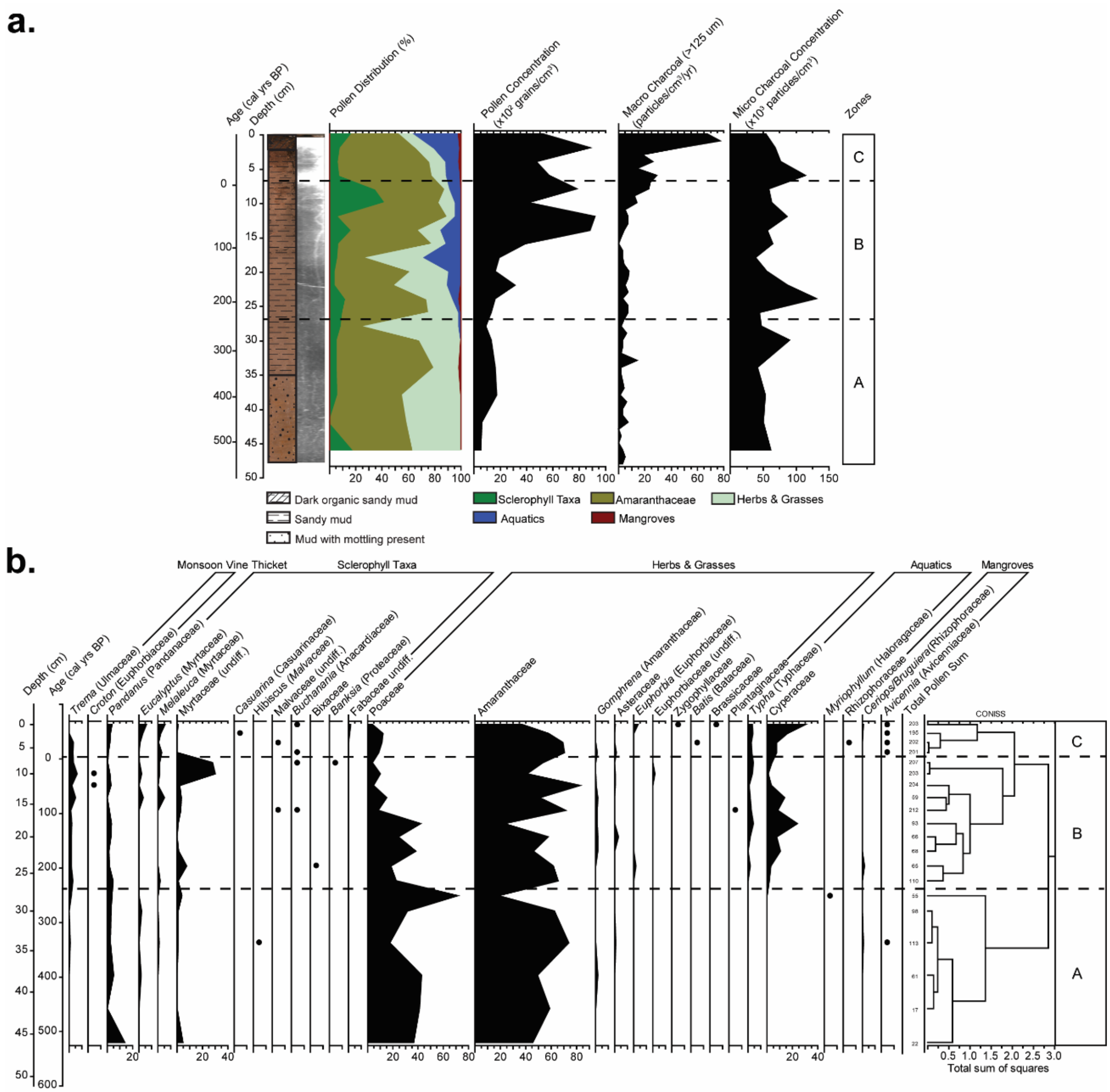

Figure 3. West Coast Swamp (WCS01) pollen and charcoal results, including (a) Summary diagram including high resolution imaging, sedimentary characteristics, pollen distribution and concentration, microscopic and raw macroscopic charcoal results. (b) Full pollen diagram plotted against age, including monsoon vine thicket, sclerophyll taxa, herbs & grasses, freshwater aquatic taxa and mangroves. CONISS defines zonations.

Core WCS01

WCS01-A: 48-26cm depth, ca. 525-225 cal. yr BP

Amaranthaceae (18-74%) initially dominated the WCS01 record. Poaceae (18-71%) peaked towards the top of Zone A, with Myrtaceaeous species (1-5%) present in low numbers. *Pandanus* (0-14%) decreased from the base of the core with *Trema* (1-2%), *Myriophyllum* (2%), *Hibiscus, A. marina* and *Ceriops/Bruguiera* (all 1%) present in Zone A. Macroscopic and microscopic charcoal accumulation was lower than at the other two sites, with a peak in microscopic charcoal at 300 cal. yr BP. Pollen concentration remained low throughout the zone (between 5-7 $x10^2$ grains/cm^3).

WCS01-B: 26cm-6cm depth, ca. 225 cal. yr BP to AD 1950

Amaranthaceae (23-82.5%) dominated Zone B while Poaceae (4-40%) declined and arboreal taxa (4-42%) including, Myrtaceae (undif.) (1-30%), *Melaleuca* (1-5%), *Eucalyptus* (1-3%), *Pandanus* (1-5%) and the monsoon vine thicket taxa *Trema* (1-6%) increased. Aquatic taxa (2-28%) increased around 200 years ago, including Cyperaceae (1-24%) and *Typha* (1-4%). Woody taxa included the monsoon vine thicket types *Croton* and Bixaceae (both ≤2%) and the open woodland *Banksia* and *Buchanania* (both <1%). Euphorbiaceae (2%), *Gomphrena* (1-2%) and Asteraceae (1-3%) were present. Macroscopic charcoal was comparable to Zone A while microcharcoal peaked at 200 cal. yr BP and began to increase from AD 1850. Pollen concentration also increased significantly after AD 1850, from 13 to 92 $x10^2$ grains/cm^3.

WCS01-C: 6-0cm depth, AD 1950 to present

Amaranthaceae (37-70%) dominated Zone C, declining towards the top of the core. Freshwater aquatics (10-34%) peaked with Cyperaceae (7-30%) and *Typha* (3-4%) present. Woodland taxa (7-17%) declined and then recovered, with increasing values of Myrtaceae types (1-6%), *Pandanus* (1-4%), and minor taxa including *Euphorbia* (3%), Casuarinaceae, Malvaceae, *Buchanania* and Fabaceae (all ≤2%). Poaceae (4-12%) and a greater diversity of savanna taxa were present including Asteraceae, *Gomphrena*, Zygophyllaceae, Brassicaceae and *Batis* (≤1%). Mangrove pollen types included *A. marina*, *Ceriops/Bruguiera* and *Rhizophora* spp (all ≤1%). Pollen concentration declined and then peaked towards the top of Zone C. Microcharcoal peaked at AD 1950 while macroscopic charcoal accumulation increased from AD 1950 and peaked around AD 2000.

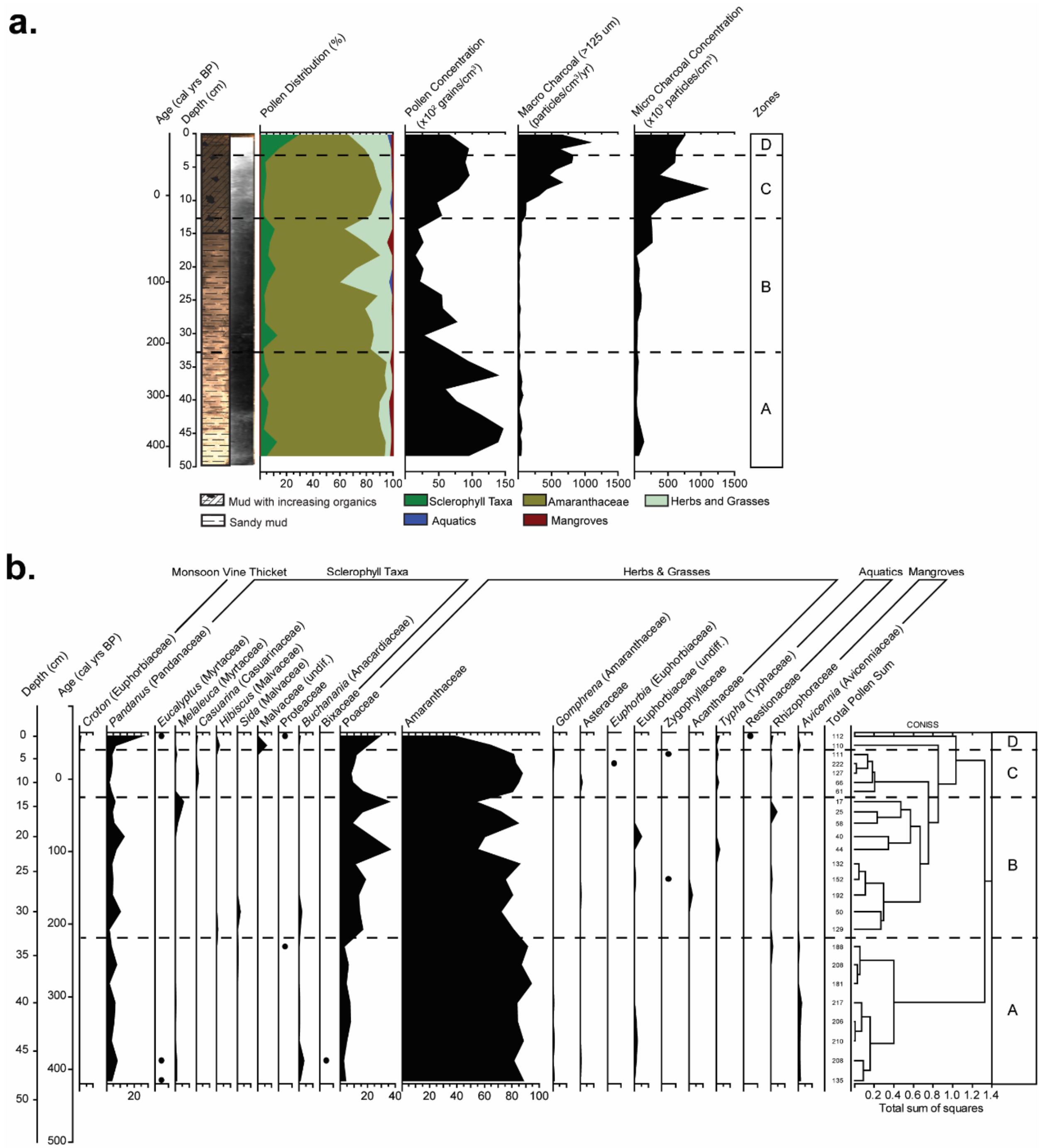

Figure 4. Well Swamp (WS01) pollen and charcoal results, including (a) Summary diagram including high resolution imaging, sedimentary characteristics, pollen distribution and concentration, microscopic and raw macroscopic charcoal results. (b) Full pollen diagram plotted against age, including monsoon vine thicket, sclerophyll taxa, herbs & grasses, freshwater aquatic taxa and mangroves. CONISS defines zonations.

Core WS01

WS01-A: 48-33cm depth, ca. 415-225 cal. yr BP

Amranthaceae (81-94%) dominated Zone A with sclerophyll herbs including Poaceae (2-7%), and *Gomphrena* (≤ 2%). Sclerophyll and monsoon vine thicket taxa (2-14%) were minor components in Zone A with *Pandanus* (3-8%), *Buchanania* (1-3%), *Eucalyptus, Melaleuca*, Bixaceae, Euphorbiaceae (undif.) and Proteaceae (all ≤ 1%) present. Mangrove types (1-2%) included *Rhizophora* and *Avicennia marina* (≤2%). Pollen concentration fluctuated and peaked in Zone A (146 $x10^2$ grains/cm^3). Macroscopic and microscopic charcoal accumulation was low, with a small peak in macroscopic charcoal from 300-250 cal. yr BP.

WS01-B: 33cm-13cm depth, ca. 225 cal. yr BP –AD 1925

Amaranthaceae (53-86%) dominated the record and Poaceae (9-35%) increased towards the top. Other savanna types included Acanthaceae and Zygophyllaceae (≤ 2%). The arboreal taxa was dominated by *Pandanus* (2-13%) with *Hibiscus, Sida* and *Buchanania* (all ≤2%) present between 200-150 cal. yr BP. *Melaleuca* (2-6%) peaked between 50-25 cal. yr BP and the aquatic *Typha* (2%), Euphorbiaceae (undif.) (1-5%) and the mangrove *Rhizophora* (1-4%) were briefly present. Pollen concentration declined to its minimum in this zone. Microcharcoal accumulation increased slightly from 150 cal. yr BP and both microscopic and macroscopic charcoal accumulation increased from AD 1950.

WS01-C: 13cm-3cm depth, AD 1925-AD 1995

Amaranthaceae (80-87%) increased as Poaceae (9-16%) decreased. Sclerophyll herbs included Asteraceae, *Euphorbia, Gomphrena* and Zygophyllaceae (all ≤ 2%). Woody taxa (3-5%) including *Pandanus* (≤ 4%), Casuarinaceae (1-2%), and *Melaleuca* (1%) were at a minimum. The aquatic *Typha* (1-2%) was intermittently present. Pollen concentration, microscopic and macroscopic charcoal accumulation significantly increased in Zone C with microcharcoal peaking at AD 1950.

WS01-D: 2-0cm depth, AD 1995 –present

Zone D was characterised by declining Amaranthaceae (38%), increasing open woodland taxa (30%) and Poaceae (29%). *Pandanus* (25%) peaked in Zone D with a greater diversity of woodland taxa present including Casuarinaceae, *Eucalyptus, Buchanania* and Proteaceae (all 1%). Aquatic taxa (3%) reached their maximum in this zone with *Typha* (2%) and Restionaceae (1%) present. Microscopic charcoal values and pollen concentration declined and macroscopic charcoal peaked at the top of WS01.

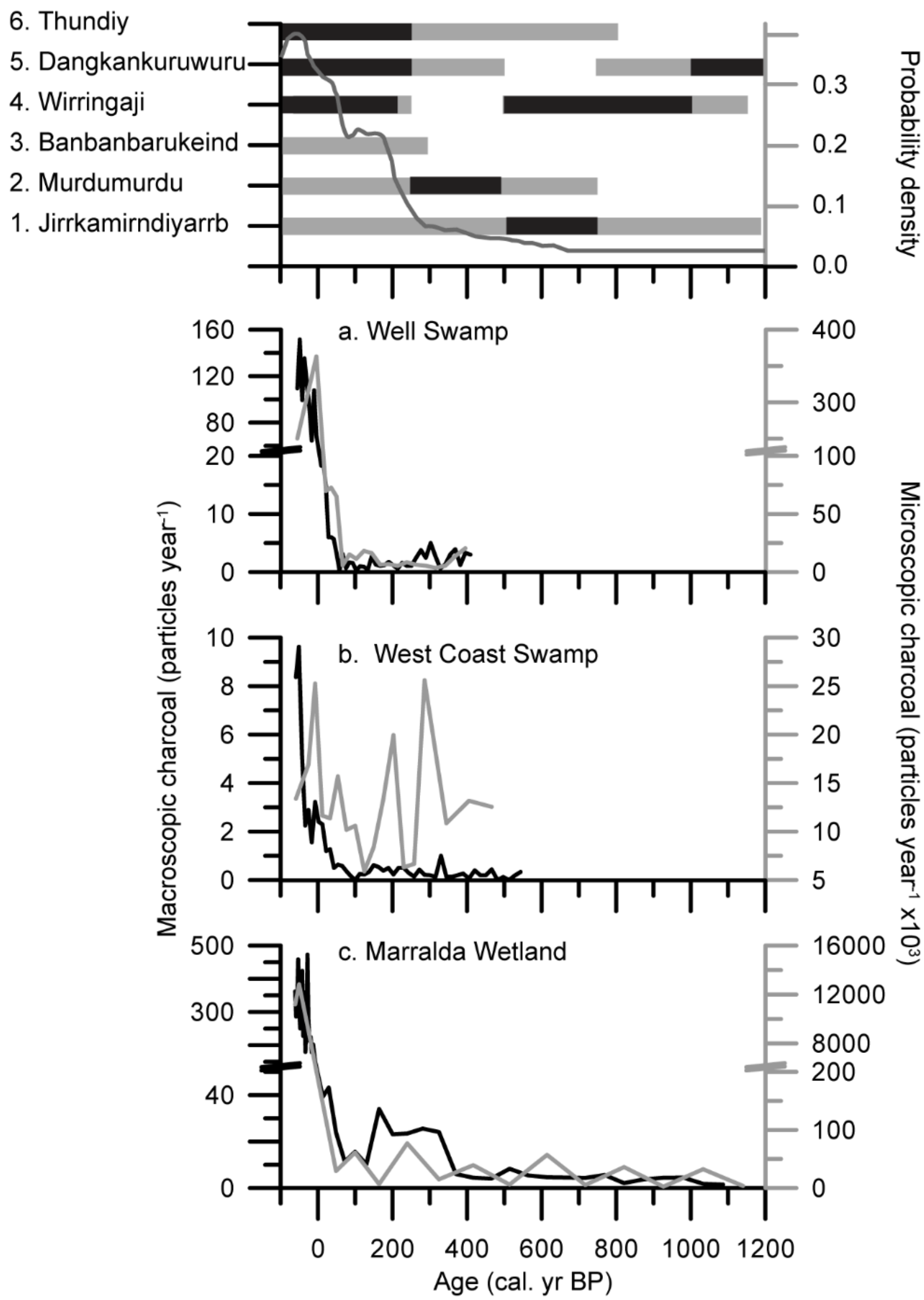

Figure 5. Archaeological evidence of human occupation and charcoal records from the South Wellesley Islands. Top panel: Occupational phases from six stratified archaeological deposits across Bentinck Island with numbers corresponding to site locations shown in Figure 1. Occupational phases (grey boxes) and periods of intensive occupation (black boxes) after (Peck, 2016; Twaddle et al., 2017). The summed probability plot of calibrated radiocarbon ages (grey line; n = 128) from the South Wellesley Islands is adapted from Memmott et al., (2016). CharAnalysis charcoal accumulation rates from (a) Well Swamp, (b) West Coast Swamp and (c) Marralda Wetland including macroscopic charcoal (particles year -1) (black line) and microscopic charcoal (particles year-1 ×103) (grey line). 0 BP refers to AD 1950.

Discussion

Late Holocene: Mangrove Contraction and Freshwater Expansion

This study of three palaeoenvironmental records from Bentinck Island examines the influence of late Holocene sea-level, prograding shorelines and effective precipitation on wetland development and vegetation evolution in tropical northern Australia. The spatial distribution of sites allows island-wide trends in vegetation development to be separated from localised changes driven by site-specific characteristics. Island-wide trends are then compared to late Holocene palaeoenvironmental records across tropical northern Australia.

Marralda Wetland (MARR04) on the southeast coast of Bentinck Island provides a 1250 cal. yr long paleoenvironmental record. The site supported a mixed mangrove community dominated by *Rhizophora* (40-50%) between 1250 and 850 cal. yr BP, with associated back mangrove taxa including *Ceriops/Bruguiera, A. corniculatum, A. marina, Excoecaria, Acanthus, Plumbaginaceae* and *Lumnitzera* (Figure 2). *The Rhizophora pollen type* is likely derived from *R. stylosa* as it is the only species of this genus recorded in the Wellesley Archipelago (Thomas and Pedley, 2005; Rosendahl, 2012). *R. stylosa* grows in mid-to-low intertidal environments, but prefers areas with freshwater availability (Duke, 2006). High values of *Rhizophora* (25-40%) pollen are recorded in supratidal and lowland coastal regions across northern Australia and the Torres Strait (Proske, 2016; Rowe, 2012), with the abundant and anemophilous pollen recorded nearly 2km upwind of the parent source (Grindrod, 1985). Therefore, *R. stylosa* is likely growing some distance from MARR04, with pollen transported to the site by the dominant onshore south-easterly wind. Other mangrove types are poorly dispersed, due to their reliance on pollinating vectors other than wind, including *Aegiceras* spp., *A. marina, Ceriops/Bruguiera* and *Excoecaria* spp. (Tomlinson and Tomlinson, 1994; Proske et al., 2014; Grindrod, 1985). *A. corniculatum* (the river mangrove) is often poorly represented in palynological studies as it produces little pollen (Mao et al., 2006; Li et al., 2008), growing on the landward margin or banks of tidal waterways (Brock, 1988). Pollen values of >5% suggest *A. corniculatum* was growing locally between 1250-850 cal. yr BP, indicating water salinity did not exceed ca. 0.5% for long periods of time (Ball, 1988). Coastal dune and beach ridge activity in the South Wellesley Islands increased from 1900 cal. yr BP (Sloss et al., 2018) with sedimentary characteristics and shell hash indicating the Marralda Wetland was periodically influenced by the marine environment until ~ ca. 900 years ago (Mackenzie et al., 2016). Coarse-grained siliciclastic sediment with abundant shell hash was also found in the final 20cm of the MARR02 core sampled by Moss et al. (2015).

Mangrove taxa declined after 900 cal. yr BP on the southeast coast of Bentinck Island, as aquatic taxa increased, indicating a transition to a brackish/freshwater wetland by c. 800 cal. yr BP. The palynological record from Marralda Wetland shows *Eucalyptus*, *Pandanus* and *Melaleuca* increased from 850 cal. yr BP, as a swamp forest and coastal woodland replaced the mangrove community. *Rhizophora* presence declined further at 400 cal. yr BP, with freshwater aquatic and woodland species increasing, indicating the final phase of freshwater swamp development. The freshwater wetland at Marralda developed around the same time as the sediment archives began accumulating sediment at West Coast Swamp (WCS01) (550 cal. yr BP) and Well Swamp (WS01) (450 cal. yr BP).

At WCS01 high values of Amaranthaceae (40-80%) suggest a hypersaline mudflat and/or saltmarsh dominated by Samphire was present after 525 cal. yr BP. Amaranthaceae (predominantly the *Halosarcia* genus) is restricted to salt marshes and coastal regions in northern Australia, with values >5% of the pollen sum indicating a nearby community (Proske, 2016; Grindrod, 1983; Proske et al., 2014). Modern pollen data found Amaranthaceae values above 40% at WCS01 and WS01 despite wetland, savanna and open woodland characterising the extant vegetation communities. This suggests Amaranthaceae pollen is transported by wind from nearby saline mudflats, overwhelming the local vegetation signal. Poaceae pollen >40% can identify local savanna in fossil records (Julier et al., 2017). At WCS01 Poaceae contributes up to 40% of the pollen sum, with relatively high *Pandanus* (3-14%) values suggesting a coastal swamp was surrounded by open savanna. A modern pollen study from the Torres Strait shows *Pandanus* is the key indicator of coastal swamps, but also grows in coastal woodland communities (Rowe, 2012). At WS01, Amaranthaceae (>80%), *A. marina* (1%) and low values of Poaceae and woodland taxa suggest a back mangrove hypersaline samphire saltmarsh environment existed after c. 400 cal. yr BP.

Melaleuca and *Typha* pollen peaked in the MARR04 core around 400 and 200 cal. yr BP respectively as an extensive wetland developed. *Typha* and Cyperaceae appeared in the WCS01 record around 250 cal. yr BP, as a freshwater swamp developed on the southwest coast of Bentinck Island. Myrtaceae, the monsoon vine thicket taxa *Trema,* and vegetation diversity increases in the WCS01 record over the last 100 years. Poaceae values increased from 200 cal. yr BP in the WS01 record as a hypersaline mudflat transitioned to the present day open savanna vegetation community. WS01 is currently a subsurface freshwater resource with *Typha* occasionally recorded in the last 100 cal. yr BP. At WS01, *Pandanus* increased significantly since AD 1900 suggesting increased moisture availability at the site. Similarly, increased evidence of swamps since AD 1950 is inferred at MARR04 from a peak in *Typha* and at WCS01 from increasing Cyperaceae.

This study finds mangroves and hypersaline mud flats transitioned to freshwater wetlands between 850-250 cal. yr BP around the coastal margins of Bentinck Island, comparable to lake and wetland expansion across tropical northern Australia. Increasing effective precipitation caused lake expansion in the last 1000 years on Groote Eylandt (Shulmeister, 1992) and allowed mangrove communities to transition to freshwater swamps around 600 years ago in the eastern Kimberley (Proske, 2016). Humification data from Black Springs found a wetter phase occurred in the last 600 years with an increase in aquatic taxa and *Pandanus* in the last ~230 years (Field et al., 2017). The expansion of freshwater sites would have provided an essential resource for expanding coastal populations in the late Holocene (Williams et al., 2010) with the number of occupation sites and rates of materials deposited increasing in the last 1000 years across northern Australia (Ulm, 2011, 2013) suggesting increasing populations (Williams et al., 2015b).

Fire Ecology and Archaeological Context

The South Wellesley Islands offer a unique opportunity to study the effect of Kaiadilt occupation and abandonment on fire regimes as there are extensive ethnographic records and archaeological sites across the islands. Archaeological research across the South Wellesley Islands has produced 128 radiocarbon dates (Memmott et al., 2016). The summed probability distribution of radiocarbon dates provides a general proxy for regional trends in occupation (Rick, 1987), which can be compared to the charcoal accumulation records to understand anthropogenic fire regimes (Figure 5). Phases of occupation and more intensive occupation (i.e. discard of more material per unit time) vary between sites with over half of the radiocarbon dates calibrated within the last 300 years (Memmott et al., 2016). Murdumurdu, near Marralda Wetland found peak occupation occurred around 300 years ago (Moss et al., 2015; Twaddle et al., 2017) and intensified occupation in the last 300 years is recorded at Wirringaji, Dangkankuruwuru and Thundiy (Figure 5) (Peck, 2016; Twaddle et al., 2017; Nagel et al., 2016). The Marralda Wetland charcoal accumulation record found local and regional fires increased between 350-150 cal. yr BP corresponding with the archaeological data. However, the earlier period of intensified occupation at Jirrkamirndiyarrb 1.2 km to the east is only reflected in the microscopic charcoal record. Both Well Swamp and West Coast Swamp see small increases in macroscopic charcoal around 300 cal. yr BP although charcoal counts are significantly lower than that found in Marralda Wetland. These results suggest that macroscopic charcoal accumulation is recording very localised human occupation phases in tropical northern Australia.

WCS01 recorded the lowest accumulation of micro- and macroscopic charcoal and the fire-sensitive vine thicket associate *Trema* (Brock, 1988) is present in the pollen record for the last 300 cal. yr BP. Scattered surface archaeological deposits, and the possible hiatus in the Dangkankuruwuru archaeological sequence (Figure 5), suggests the region around West Coast Swamp may have only been visited periodically. However, the South Wellesley Islands hold the highest density of fishtraps in Australia, with an extensive network present on Kirk Point roughly 3km south of West Coast Swamp (Memmott et al., 2008). The charcoal, pollen and archaeological data suggests less burning occurred in the southwest region of Bentinck Island, highlighting the spatial variability in anthropogenic land-use and fire regimes across the island.

Charcoal accumulation significantly increased at all sites around AD 1900 disrupting the earlier anthropogenic fire regime characterised by low fire activity. Glass artefacts found on the surface of Jirrkamirndiyarrb and Murdumurdu (Ulm et al., 2010) continued to be used by Kaiadilt people throughout the late nineteenth century and the first half of the twentieth century until people were removed in 1947/1948 (Tindale, 1962a, 1962b). 'Corrective burning' may explain the change in fire regimes on Bentinck Island as permanent human occupation changed to periodic visitation typically occurring during the drier months from the 1980s onwards. In the Northern Territory Haynes (1985: 210) found when people were able to access areas the desire to clean country "is regarded as being so important that the season is overlooked and intense fires have ensued." Ethnographic records support this interpretation, with Norman Tindale noting the Kaiadilt traditionally fired grasslands each year, however a large area along the southeast coast was burnt after 12 years absence in 1959, "restoring a semblance to the conditions they had maintained for many centuries" (Tindale, 1962a: 280). The linguist Nicholas Evans (Australian National University, pers. comm., 2013) visited Bentinck Island in September 1982 and recorded people systematically burning the South Wellesley Islands, saying it was later in the season than ideal, but that the long absence of people from the island left them no choice. The charcoal records show that the removal of Kaiadilt people from the South Wellesley Islands increased the fire activity and area burned as large fires occurred outside of the early dry season. In open grassy woodlands short-lived fires may leave less of a signal in charcoal records than fires which reach the canopy (Jensen et al., 2007). The significant increase in charcoal accumulation after AD 1900 may also be due to a change in the types of fires occurring rather than a change in the fire frequency or area burned.

The vegetation of tropical northern Australia is significantly affected by fire (Bowman, 2002) with palaeoenvironmental records from islands in the Gulf of Carpentaria (Prebble et al., 2005; Shulmeister, 1992) and the Torres Strait (Rowe, 2006, 2007) finding fire influenced vegetation distribution and composition during the Holocene. The vegetation response to increased fire in the South Wellesley Islands was subtle and depended on the local floristic assemblage. Myrtaceae was dominant at Marralda Wetland during the last c. 50 cal. yr BP, with woodland diversity increasing including Sapindaceae sp, Malvaceae sp, *Buchanania, Banksia* and Loranthaceae. Poaceae values were relatively low, suggesting a closing of the canopy cover as woodland taxa diversified, despite higher fire activity. In dry areas, monsoon vine thicket predominantly occurs in fire shadows (Shulmeister, 1994), and on Bentinck Island it is often protected on its southeast side from the predominant wind direction in the dry season. Monsoon vine thicket is under-represented in the pollen rain as the dominant taxa have poor pollen dispersal, with trace levels of *Croton, Trema* and others in the pollen assemblage indicating the presence of vine thicket taxa (Rowe, 2012; Burn et al., 2010). Monsoon vine thicket indicators are present at Marralda Wetland in the last 100 years, with the fire-sensitive taxa suggesting fires were either low intensity or infrequent, or dense patches were protected by the sand dunes and wetlands or by people protecting these resources.

At West Coast Swamp *Eucalyptus, Melaleuca*, *Pandanus* and Poaceae increased slightly from AD 1950. Similarly, Poaceae and *Pandanus* increased around AD 1995 at Well Swamp. *Pandanus* is a wetland indicator, however it also grows in coastal woodlands and has been used to indicate localised disturbance as it is fire tolerant (Prebble et al., 2005; Rowe, 2015). The subtle floristic changes at Well Swamp and West Coast Swamp may be driven by increased fire events as frequent fires are thought to have induced and maintained savanna vegetation at the expense of forest in tropical Australia (Hoffmann et al., 2012; Murphy and Bowman, 2012). In the 1980s, outstations were constructed in several locations on the western side of Bentinck Island bringing more opportunities for people to use fire technologies in this part of the island. However, frequent landscape burning in savanna ecosystems may cause structural, but not floristic, changes to vegetation as taxa are tolerant to recurrent burning (Bowman et al., 1988). While there are no clear shifts in the pollen assemblages to suggest changing fire regimes affected the composition of vegetation communities it may have affected the vegetation structure (Bowman et al., 1988). This study highlights the importance of charcoal analyses when evaluating the role of fire and climate in shaping extant vegetation communities in tropical northern Australia.

Conclusion

Results from the palynological and charcoal study of sediment cores MARR04, WCS01 and WS01 record the vegetation and fire history of Bentinck Island during the late Holocene. Palynological results show initial changes in vegetation are driven by late Holocene sea level regression and coastal progradation. On the southeast coast a diverse mangrove community developed, with freshwater and sediment supplied by a tributary while the southwest and northeast coast sites developed first as hypersaline mudflats dominated by samphire. Wetland development occurred at Marralda Wetland after 850 cal. yr BP and across the region around 250 cal. yr BP. This study highlights the importance of coupling regional and local charcoal records with palynological studies in regions where vegetation is adapted to fire, as pollen assemblages may not reflect local changes in fire activity. Charcoal analysis found that fire events significantly increased in the 1900s, when Kaiadilt fire practices were disrupted, and the South Wellesley Islands were depopulated. The pollen assemblages showed little vegetation change in response to the significant shift in the fire regime, suggesting wetland expansion, woodland diversification, fire-tolerant taxa and the fire technologies deployed by Kaiadilt people limited the effect of fire on vegetation distribution and composition in the South Wellesley Islands.

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ORCID iDs

Lydia Mackenzie https://orcid.org/0000-0003-4842-3021

Sean Ulm https://orcid.org/0000-0001-6653-9963

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