

Implications of sea level variability on the formation and evolution of subtropical Rainbow Beach patterned fen complexes, Queensland, Australia

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Johanna M Hanson,^{1,2} Kevin J Welsh,¹ Patrick T Moss¹
and Patricia Gadd³

Abstract

The Great Sandy National Park [K'gari (Fraser Island) and Cooloola] contains the largest subtropical patterned fen complexes in the world. These globally significant, groundwater-dependent ecosystems have been previously studied in relatively undisturbed areas on K'gari and were suggested to be resilient to changes in hydrology, sea level and wildfires. The Rainbow Beach patterned fens are under-studied systems thought to be formed in local perched aquifers. The palaeoenvironmental conditions required for the formation and continuation of these peatlands, and how they react to changes in hydroclimate, sea level and human activities are uncertain. We attempt to resolve this ambiguity using proxies for vegetation and environmental changes over the last ~12,770 cal yr BP from a sediment core located in the Rainbow Beach patterned fen complex. We infer the formation of an aquitard layer and *Empodisma minus* mire development at ~12,770 cal yr BP, with conditions conducive for patterning ~12,000–10,000 cal yr BP. Paludification occurred in the early Holocene, coincident with increased sea levels, which expanded the mire inland. Increased salt marsh taxa during this period coincides with decreased *E. minus* values, while further peatland development occurred ~4200 cal yr BP, suggesting that marine influences greatly effect these coastal peatlands. Evidence of vegetation thickening associated with post-European fire suppression was observed. Compared to those on K'gari, the Rainbow Beach complex appears to have initiated through different processes and show greater sensitivity to changes in sea levels. Therefore, subtropical patterned fens should be assessed independently to identify individual trajectories and sensitivities.

Keywords

Empodisma minus, groundwater-dependent ecosystems, fire regimes, mire, sea level, vegetation thickening

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Introduction

The Great Sandy National Park (GSNP) situated in southeast Queensland, Australia, consists of World Heritage-listed K'gari (Fraser Island) and Cooloola. Both Cooloola and K'gari are host to a range of globally important wetlands, including the patterned fen complexes (Fairfax et al., 2011). These are significant refuges for a wide variety of threatened and endangered species (e.g., the eastern ground parrot, Cooloola sedge frog, Oxleyan pygmy perch, grey goshawk etc.; Lindsay, 2013; Moss et al., 2016; Twyford, 1996).

The GSNP patterned fen complexes are freshwater minerotrophic peatlands that consist of hummocks (ridges and strings) and pools (flarks) which are orientated perpendicular to the groundwater flow and parallel to the slope of the land (Fairfax et al., 2011; Moss et al., 2016). These systems form in nutrient deficient sediment and require acidic and anoxic groundwater for fen formation (Agnew et al., 1993; Fairfax and Lindsay, 2019; Moss et al., 2016). The subtropical patterned fen complexes in the GSNP are globally unique systems as they form by the growth of restiad species *Empodisma minus*, unlike other patterned fen complexes which mainly form from the growth of the pteridophyte *Sphagnum* (Fairfax and Lindsay, 2019; Moss et al., 2016). Like *Sphagnum*, this restiad has been suggested to be an ecosystem engineer (Hodges and Rapson, 2010).

The majority of research on subtropical patterned fens has been conducted on the two complexes (Moon Point and Wathumba)

located on K'gari. These complexes are located in protected areas and are therefore relatively undisturbed ecosystems situated away from human settlements. The Moon Point patterned fen complex is located adjacent to the Pleistocene aged dune sequence 'Awinya' (Patton et al., 2019). Moss et al. (2016) proposed that the Moon Point complex was initially a deep perched lake (~35,000 cal yr BP) which shallowed and infilled forming a mire conducive to patterning (~12,000 cal yr BP). This was determined by changes in sedimentology from silt to clay to peat (which showed increased mire taxa). This shift to peatland conditions was attributed to either a change in climate during the Last Glacial Interglacial Transition

¹School of Earth and Environmental Sciences, The University of Queensland, Australia

²School of Earth and Environment, University of Canterbury, New Zealand

³Australian Nuclear Science and Technology Organisation, Lucas Heights, Australia

Corresponding author:

Johanna M Hanson, School of Earth and Environmental Sciences, The University of Queensland, Brisbane, QLD 4072, Australia and School of Earth and Environment, University of Canterbury, Christchurch, 8041, New Zealand.

Email: johanna.hanson@pg.canterbury.ac.nz

(LGIT, ~18,000–12,000 cal yr BP; Petherick et al., 2013) which generally showed warmer and wetter conditions than those of the Last Glacial Maximum (LGM, ~22,000–18,000 cal yr BP; Petherick et al., 2013) or may be simply as a result of infilling of a lacustrine environment (Moss et al., 2016).

The Wathumba patterned fen complex sits adjacent to Holocene aged dune sequence ‘Triangle Cliff’ (Patton et al., 2019), with the Wathumba creek running through the complex. Two peat cores were extracted from Wathumba providing a basal age of ~4300 cal yr BP. This second phase of peat growth on K’gari was suggested to be due to declining sea levels from the mid-Holocene highstand, with Restionaceae (*E. minus*) quickly dominating the pollen record, likely indicating rapid patterning of the mire. This study shows that the initiation processes of the K’gari patterned fen complexes differ between sites, however once formed, they appear to be relatively stable ecosystems. This is corroborated by Fairfax et al. (2011) who used aerial photography from 1958 to 2010 on the K’gari patterned fens which showed no significant changes. The subtropical patterned fens on K’gari are thought to be resilient to both sea level variability and fires due to the *E. minus* protecting the underlying peat (Fairfax et al., 2011; Moss et al., 2016). A more recent analysis has shown a reduction in patterned fen extent due to vegetation thickening between 1958 and 2016 (Stewart et al., 2020). Peatlands are most at risk of ignition during periods of water deficit, with the peat located on the edges of the mire more susceptible to drying out (Fairfax and Lindsay, 2019). The recommended fire frequency for wet heath (which surrounds the patterned fens) has been suggested to be between 8 and 20 years (Queensland Herbarium, 2019). Fairfax and Lindsay (2019) proposed the *E. minus* wetlands may in fact require a different fire frequency, while Stewart et al. (2020) recommended a fire frequency of 12 years.

Unlike the patterned fen complexes on K’gari, there has been limited research conducted on the Rainbow Beach patterned fen complex in Cooloolool. In 1955, Coaldrake (1961) sampled and described an acid peat profile (305 cm deep), collecting six bulk samples: four peat samples and the other two from the underlying peaty sand. Coaldrake (1961) initially suggested the base of the profile represented the palaeo-valley floor. Nearly 50 years later, these archived samples were utilized for a low resolution, multi-proxy geochemical analysis by Krull et al. (2004). Bulk sediment from the two peaty sand samples were used for AMS ^{14}C analysis and provided an approximate basal age of $18,580 \pm 120$ BP (calculated to 20,925 cal yr BP using SHCal20 in OxCal; ver. 4.4, Bronk Ramsey, 1995; Hogg et al., 2020). Krull et al. (2004) suggested a shift in fire regimes from the Pleistocene-early Holocene (high fire frequency) to the early-middle Holocene (lower fire frequency), which was indicated by an abrupt decrease in aromatic C values. This study also suggested that during the LGIT to early Holocene the Carlo Creek catchment was impacted by rising sea levels and increased temperatures. During the middle to late Holocene a higher water table than present was inferred from highly depleted ^{13}C organic matter and high alkyl C (lipid) content (Krull et al., 2004). A return to drier conditions was suggested to occur in the Carlo Creek catchment during the late Holocene.

The formation processes of the Rainbow Beach patterned fens are not well understood due to the limited data availability, and it is not known whether they developed in a similar manner or responded to environmental stimuli as those on K’gari. Here we examine the formation of the Rainbow Beach patterned fen complex and how this ecosystem reacts to changing sea levels, influence of climate change and human activity.

Regional setting

The climate of the GSNP is dominated by wet summers and dry winters (BOM, 2019) and influenced by El Niño-Southern

Oscillation (ENSO) (Petherick et al., 2013). This inter-annual climate phenomenon causes drier conditions with a negative Southern Oscillation Index (El Niño) and wetter conditions with a positive Southern Oscillation Index (La Niña) in subtropical Australia, including the GSNP (Kelly et al., 2019; Petherick et al., 2013).

The Rainbow Beach patterned fen complex is situated in the subtropics along the Queensland coast approximately 200 km north of Brisbane (Figure 1a and b). It is located in the Carlo Creek catchment which lies to the west of the Cooloolool Sand Mass, a transgressive and parabolic dune system composed of highly acidic podzol soils (Thompson, 1992). The dune field is approximately 0.5–12 km wide with a length of around 40 km (Thompson, 1992) and is oriented SW to NE on a bedrock of Jurassic aged sandstone (Thompson, 1992; Thompson and Moore, 1984).

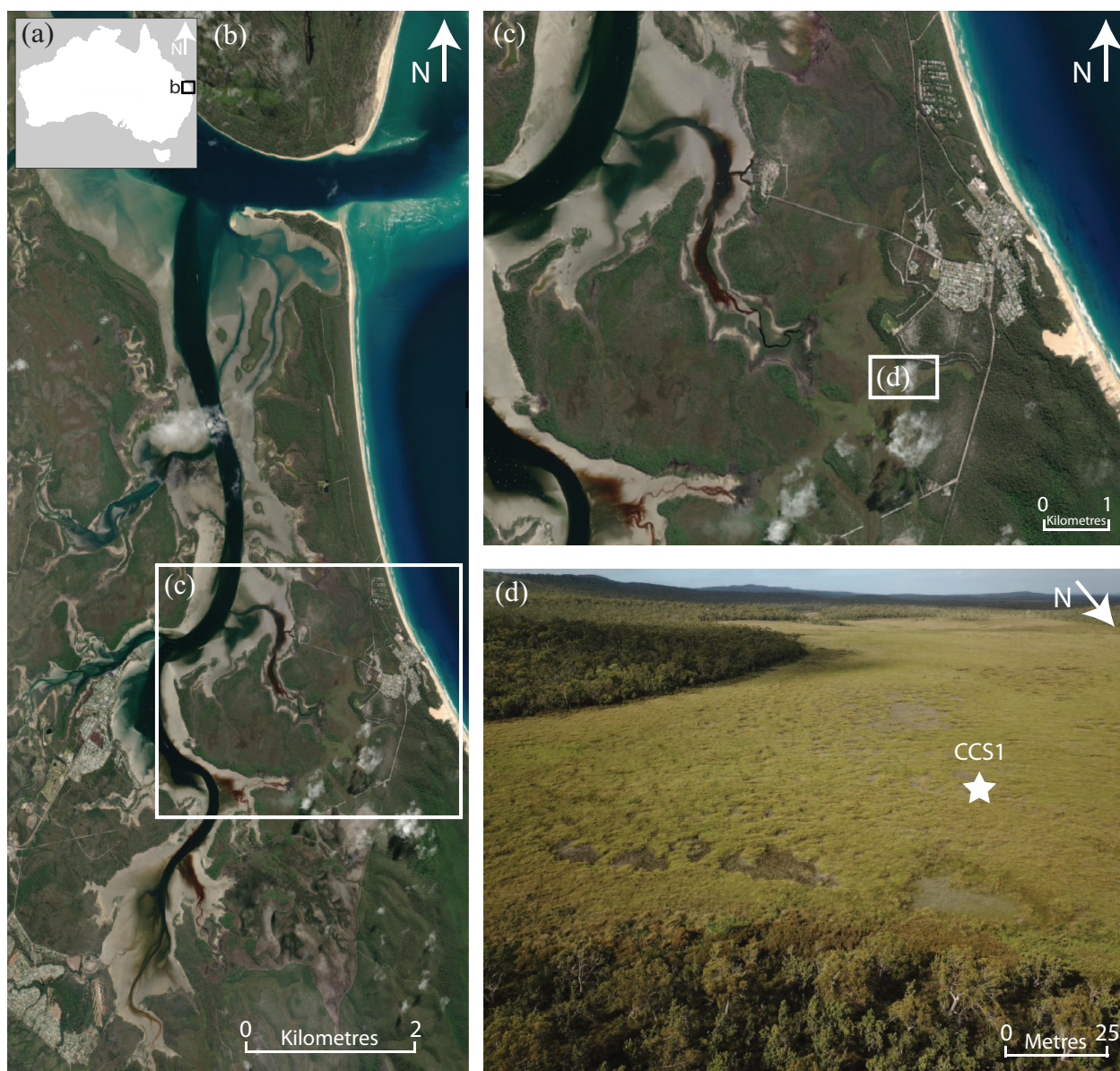
The Carlo Creek catchment (~3 m above sea level) is an internationally important coastal wetland which contains both patterned fens and non-patterned mires (Ramsar-listed; Convention on Wetlands of International Importance; Department of Agriculture, Water and the Environment, Australian Government, 2019; Krull et al., 2004; Moss et al., 2016). This is one of the largest subtropical patterned fen complexes in the GSNP (Fairfax and Lindsay, 2019; Moss et al., 2016) and is situated southwest of the Rainbow Beach township (Figure 1c and d). The Rainbow Beach patterned fens [initially described as humus podzols and acid peats (Coaldrake, 1961), later termed Nilkan (Thompson and Moore, 1984)] are potentially impacted by weed invasion, pest animal species, as well as pollution from urban areas and the nearby refuse centre (Moss, 2014).

The Cooloolool Sand Mass is host to a large regional aquifer and several smaller perched aquifers which overly the regional aquifer (Reeve et al., 1985). Based upon a water chemistry study of the Rainbow Beach patterned fens, these fens have been suggested to be a coastal perched system due to the similarities to other perched lakes around Cooloolool (McDougall et al., 2017). As these patterned fens are a coastal groundwater-dependent ecosystem (GDE), saline water from Tin Can Bay through Carlo Creek also flows into this complex. Water levels in perched aquifers in similar sand masses, such as K’gari, are thought to be highly variable due to changing climatic conditions (Hadwen and Arthington, 2011) and therefore, it may be that the Rainbow Beach patterned fens also have high water level variability. Whilst it has been suggested that the Moon Point patterned fens on K’gari were initially a perched lake (Moss et al., 2016), it is not known for certain whether the K’gari patterned fens are dependent on perched or regional aquifers. The analysis of the Rainbow Beach patterned fens should demonstrate the sensitivity of coastal GDE’s, which rely upon local perching above aquitards, over time.

Methods

Sedimentology and chronology

A 210 cm peat core (CCS1) was extracted via Russian d-section in 2018 in the Rainbow Beach patterned fen complex located in the Carlo Creek catchment (S25°55’11.7”, E153°04’39.1”) (Figure 1c and d), which is in the approximate vicinity of the sampled peat profile by Coaldrake (1961) and Krull et al. (2004). The core was described using the adapted version of Troels-Smith peat classification (Kershaw, 1997; Troels-Smith, 1955). Bulk sediment samples from depths 210–207.5 cm, 142–140 cm and 71.5–69 cm were sampled, with charcoal and plant material used for radiocarbon dating (Table 1). Using OxCal (ver. 4.4, Bronk Ramsey, 1995, 2008, 2009), the returned ages were calibrated using the Southern Hemisphere calibration curve (SHCal20; Hogg et al., 2020). An age-depth model was



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/ Airbus DS, USDA, USGS, AeroGRID, IGN and the GIS User Community and Dr. Kevin Welsh

Figure 1. (a) Map of Australia highlighting Cooloolool in southeast Queensland. (b) Satellite image of Cooloolool and Tin Can Bay. (c) Satellite image of the Rainbow Beach township and the Carlo Creek catchment. (d) Location where sediment core CCS1 was extracted in the Rainbow Beach patterned fens (drone photo by Dr. Kevin Welsh).

Table 1. A description of material dated, the returned conventional ages from Beta Analytic, calibrated ages using OxCal (Bronk Ramsey, 1995) and the ages produced from the age-depth model created using rbacon (Blaauw and Christen, 2011) in R (R Core Team, 2022).

Laboratory codes	Depth (cm)	Material	Conventional radio-carbon age (BP)	Error	OxCal calibrated age (cal yr BP) (SHCal20)	Calibrated median ages from rbacon model (cal yr BP)
Beta-502661	69–71.5	Plant	130.36	0.49	–62–25 (1883–1925 cal yr AD)	2142
Beta-502662	140–142	Plant	5070	30	5661–5901	5791
Beta-492724	207.5–210	Charcoal	10,720	40	12,626–12,739	12,722

created using the package rbacon (v.2.5.8) in R (v.4.2.0; Blaauw and Christen, 2011; R Core Team, 2022).

X-ray Fluorescence

CCS1 was scanned using an Itrax micro-X-ray Fluorescence (μ XRF) core scanner at the Australian Nuclear Science and Technology Organisation (ANSTO), Sydney. X-ray Fluorescence (XRF) is a non-destructive, high-resolution method which

measures the elemental composition of a core. Itrax measured 35 elements, however, only three elements were of interest to interpret site changes. The immobile elements titanium (Ti) and silicon (Si) were used as proxies for terrigenous sediment input (Burrows et al., 2016; Kylander et al., 2011). Iron (Fe) is a redox sensitive element as it can be oxidized from the soluble Fe^{2+} to the insoluble Fe^{3+} and therefore may be suitable as a proxy for changes in redox conditions brought about by fluctuations in the water table when normalized to Ti (Fe/Ti) (Kylander et al., 2013;

Schitteck et al., 2016). The molybdenum incoherent (Compton) to coherent (Rayleigh) (Mo inc/coh) scattering ratio was used as an indication of organic matter content (Evans et al., 2019).

Total organic carbon, carbon to nitrogen ratio and humification

Samples were extracted every 5 cm along the core for total organic carbon (TOC), carbon to nitrogen ratio (C:N) and humification analyses, except for the top 20 cm where most of the core consisted of modern roots. Meyers and Teranes (2001) method was followed for TOC and C:N. Samples were dried and crushed into an homogenous powder. Tin foil pills containing 0.1 g of the samples were analyzed for TOC and C:N using an Elementar MACRO cube elemental analyzer. For quality assurance and control, blanks and phenylalanine standards were used at the beginning, end, as well as after every 20 samples so as to limit the carry-on carbon effect.

An additional 0.2 g of the powdered samples was used for humification analysis (Chambers et al., 2012). Humification analysis was used to indicate the rate of decomposition of the peat, which can provide information on past surface wetness downcore (Chambers et al., 2011). Initially, 100 mL of 8% sodium hydroxide was added to each sample and then left to simmer on a hot plate for 1 h at ~95°C. Each sample was then decanted and diluted with deionized water into three different sized volumetric flasks (200 mL, 50 mL, and 100 mL, respectively), with samples filtered through Whatman's no. one grade filter paper after the second dilution. Samples were then pipetted into a 96-spaced microplate, which was placed into a BioTek Synergy HT microplate reader for analysis. Triplicate analysis was run using standards of deionized water and sodium hydroxide. A three-point moving average was utilized to remove any significant outliers and the data were detrended using a fourth order polynomial to remove the effects of the acrotelm, where the peat contains non-decomposing, living plants (Burrows et al., 2016; Chambers et al., 2012). Data are recorded in corrected transmission residuals (CTR), where the lower the value, the greater degree of peat decomposition (humification).

Palaeoecology

Bulk 1 cm³ samples were extracted every 10 cm (starting at 20 cm due to modern root mass) for pollen and micro-charcoal analyses. Samples were prepared using an adapted version of van der Kaars (1991) technique (Moss, 2013). Sediments were disaggregated using sodium hexametaphosphate then sieved to <180 µm. Using a heavy liquid solution (sodium polytungstate; specific gravity 1.9), the organic particles were separated from the inorganic fraction. Acetolysis, a 9:1 mL ratio of acetic anhydride and sulphuric acid, was then conducted to remove excess cellulose. Samples were mounted on glass slides and counted using a Leica DM1000 microscope at 400× magnification. An exotic *Lycopodium clavatum* pill (with a known amount of pollen (9666)) was added at the beginning of the process to quantify the concentrations of pollen and micro-charcoal (Wang et al., 1999). For statistically significant results, 300 pollen grains and 200 micro-charcoal particles (>5 µm) were counted (Finsinger and Tinner, 2005). The data were plotted using Tilia (v.2.6.1) which utilizes Constrained Incremental Sum of Squares (CONISS) to determine biostratigraphic zones from within the data (Grimm, 1987).

Results

Stratigraphy and chronology

As per the adapted Troels-Smith peat classification (Kershaw, 1997; Troels-Smith, 1955), sandy peat occurred at the base of CCS1 (210 cm) and continued until 185 cm. Between 185–65 cm

the core was dominated by humified peat. From 65 to 20 cm the fresh black peat contained fibrous root mass (*E. minus*). The top 20 cm was dominated by modern root systems with little to no peat (see Table 1 in Supplemental Material). The basal age of CCS1 was determined to be ~12,680 cal yr BP (Table 1). At ~140 cm an age of 5780 cal yr BP was determined and at ~70 cm an age of ~43.5 cal yr BP (~1900 cal yr AD) was returned. The youngest radiocarbon age could not fit the age-depth model, likely due to younger carbon contamination associated with modern roots (Figure 2). The exotic taxon *Pinus* was identified between 30 and 20 cm and was used in the age-depth model to constrain the top of the core, as an indicator of European presence within the landscape. Pine logging was a major European activity during the 1860s (McNiven, 1991) and therefore this age was used in the age-depth model.

X-ray Fluorescence

Titanium and silicon. The base of the core recorded high values of Ti and Si which decreased at ~165 cm (Figure 3). Ti and Si remained relatively diminished until ~120 cm where both elements showed a peak until ~100 cm. After 100 cm values remained relatively low, however, small fluctuations occurred towards the top of the record. At ~70 cm both Ti and Si showed a small peak. Both Ti and Si showed minimal fluctuations to the top of the record.

Iron/titanium. At the base of the core Fe/Ti values remained low until ~165 cm (Figure 3). There was a gradual increase with a broad peak at 125 cm, before values showed greater variability with an increasing trend at the top of the record, where Fe/Ti peaked to its highest values.

Molybdenum incoherent/coherent. Mo inc/coh showed its lowest values at the base of the core, before increasing at ~140 cm (Figure 3). Values plateaued to ~110 cm, before they slightly decreased to 90 cm. There was an increasing trend to the top of the record.

Total organic carbon, carbon to nitrogen ratio and humification

Total organic carbon. For the majority of the record, TOC values showed an upward trend (Figure 4). At the base of the core TOC percentages were low (~12%), however depicted a gradual increase to ~20% at 191 cm, before values slightly diminished to ~18% at 181 cm. Percentages then peaked to 26% at 145 cm and remained high until 111 cm where percentages slightly diminished to ~21% at 91 cm. Between 91 and 21 cm TOC values gradually increased with minor fluctuations.

Carbon to nitrogen ratio. At the base of CCS1 C:N showed its highest values throughout the record (~55) (Figure 4). Values recorded a decreasing trend to ~30 (145 cm), before they increased to ~33 (121 cm). Between 115 and 102 cm values fluctuated, ranging between ~29 and 35. From 95 to 61 cm C:N values once again decreased (from ~31 to ~19, respectively) before showing a gradual upward trend to the top of the record (~24).

Humification. The base of the core showed lower CTR values (Figure 4), which increased at ~175 cm. CTR values then decreased to 100 cm, before increasing to the top of the record.

Palaeoecology

Zone 1: 210–185 cm; ~12,770–10,300 cal yr BP. Zone 1 showed a shift from open herbland conditions dominated by Asteraceae

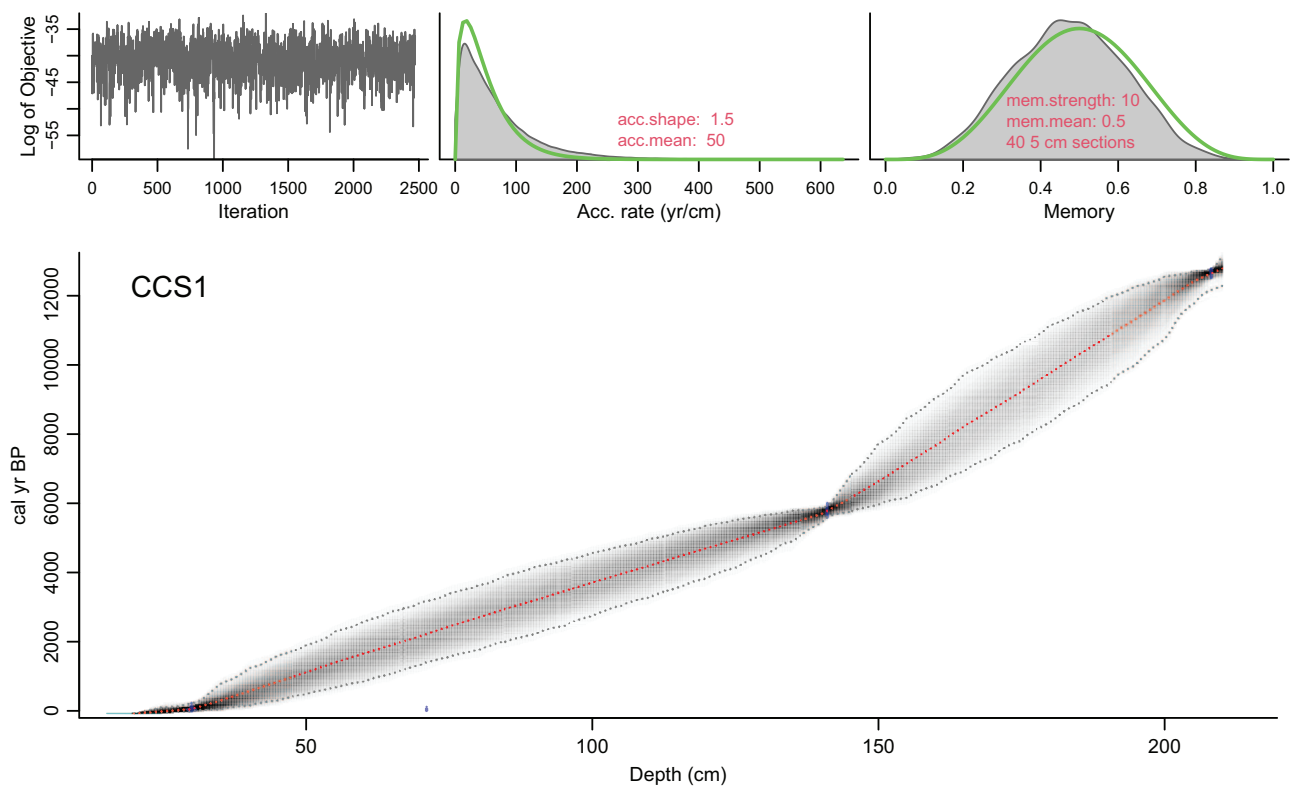


Figure 2. Age-depth model created using rbacon in R (Blaauw and Christen, 2011; R Core Team, 2022), with the blue dots indicating the radiocarbon ages used in the model. Note the age at 70 cm which did not fit the model. The red dashed line represents the model's best fit, with the grey dashed lines displaying the 95% confidence intervals.

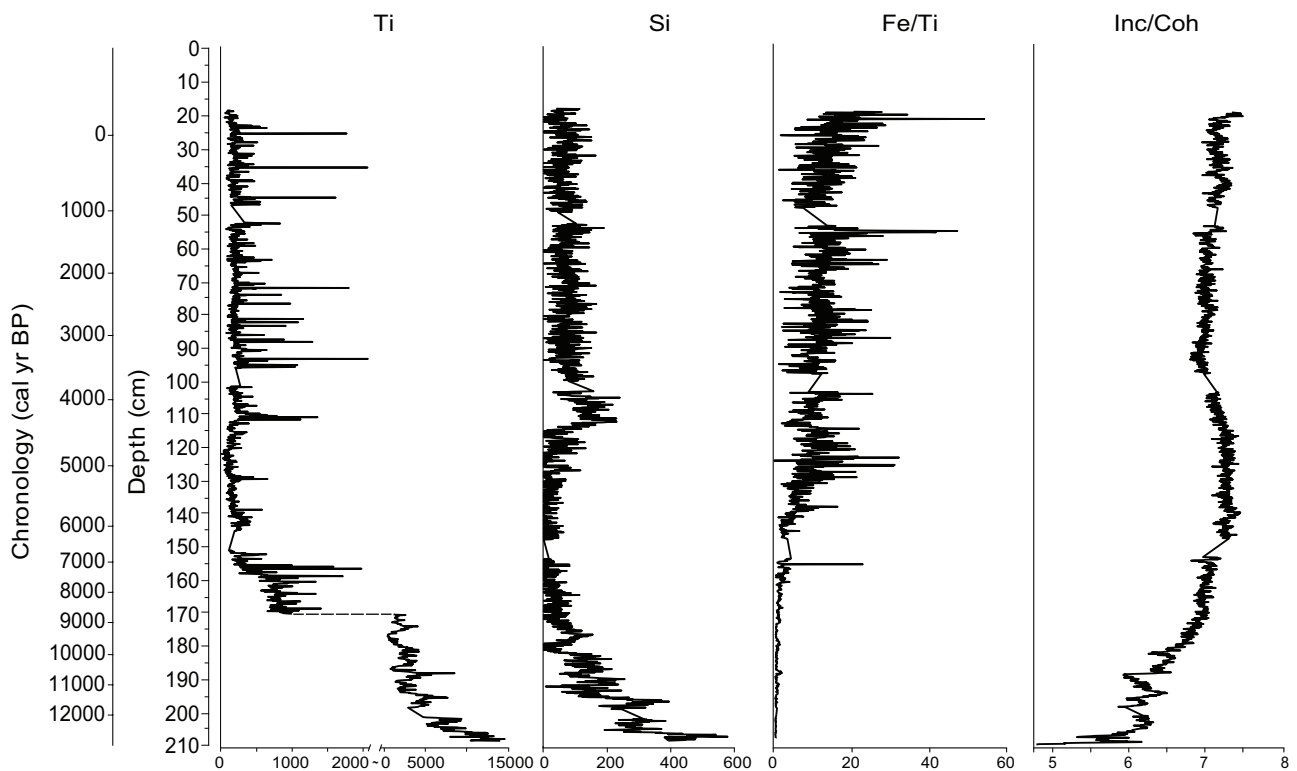


Figure 3. Itrax data graphed with age-depth model as chronology.

(Tubuliflorae), Poaceae, *Plantago* and Amaranthaceae (~75% at 209 cm to ~48% at 190 cm), to open sclerophyll woodland (~20% at 209 cm to ~45% at 190 cm), in particular with increased arboreal species *Eucalyptus*, Casuarinaceae and Ericaceae representation (Figure 5). There was an increase in aquatic taxa

(~41%–58%; dominated by *Myriophyllum*, Restionaceae (most likely *E. minus*), and Cyperaceae). This zone contained a large variety of pteridophyte taxa in small quantities (~2%), while rainforest taxa showed minimal values (~3%). Micro-charcoal values were low with a slight decreasing trend.

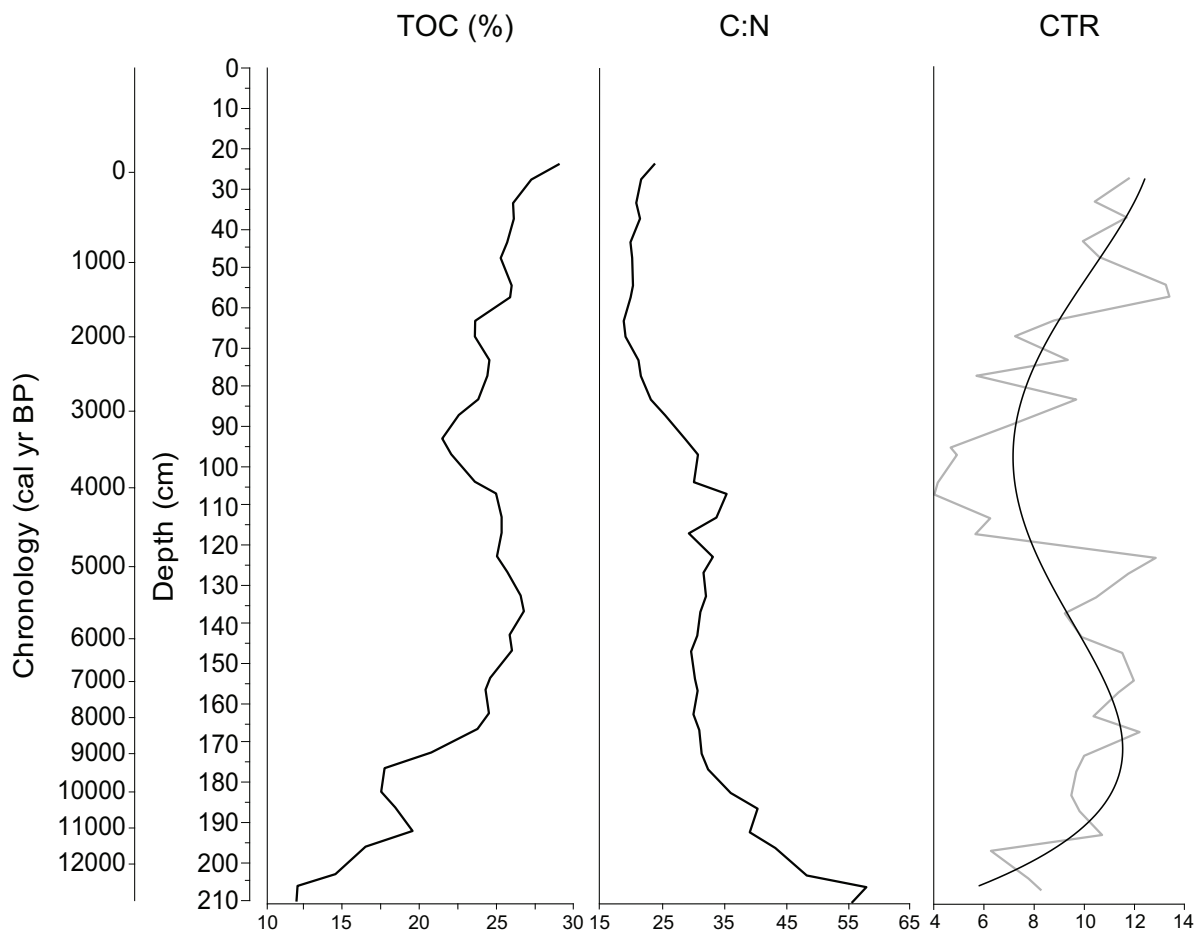


Figure 4. Total organic carbon (TOC), carbon to nitrogen ratio (C:N) and corrected transmission residuals (CTR) raw data overlain by a fourth order polynomial against the age-depth model as chronology and depth.

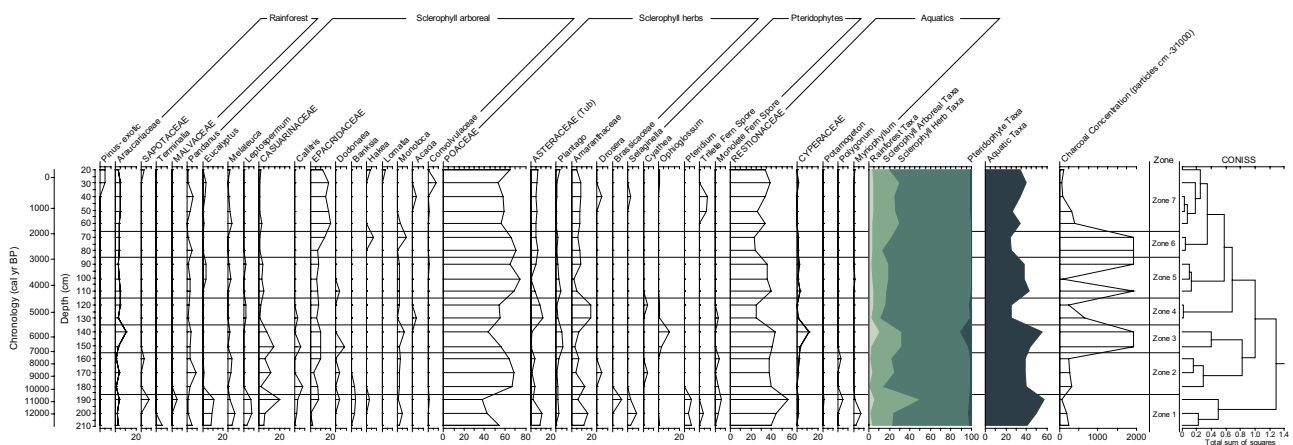


Figure 5. Pollen diagram with micro-charcoal and Constrained Incremental Sum of Squares (CONISS) zones, against depth and chronology.

Zone 2: 184–156 cm; ~10,300–7200 cal yr BP. Zone 2 was dominated by high values of herbs (~79%), in particular Poaceae (grasses), Asteraceae (Tubuliflorae) and Amaranthaceae. Casuarinaceae, Ericaceae, *Pandanus* and *Callitris* dominated the sclerophyll arboreal taxa, which as a group showed diminished values (~19%). Rainforest values continued to remain low with small fluctuations (~2%), while aquatic taxa values were decreased and plateaued for the entirety of Zone 2 (~39%). Micro-charcoal values slightly peaked at the base of this zone before decreasing again.

Zone 3: 155–135 cm; ~7200–5500 cal yr BP. Zone 3 recorded the highest values of rainforest taxa (driven by *Araucaria*; 7%)

and pteridophytes (*Ophioglossum*; ~7%). Aquatic taxa (Restionaceae and Cyperaceae) also peaked (~6%). Grasses sharply dropped to ~50%, while *Plantago* peaked (~6%). Sclerophyll arboreal taxa showed an increasing trend (~25%), dominated by Casuarinaceae and Ericaceae. Micro-charcoal peaked to its highest concentration thus far and was maintained for the entirety of this zone.

Zone 4: 135–115 cm; ~5500–4500 cal yr BP. Rainforest taxa abundance sharply declined, which remained at relatively low values for the rest of the record (~3%). Low values of sclerophyll arboreal taxa occurred, with Ericaceae and Casuarinaceae making up the majority of arboreal taxa (~11%). Grasses showed a

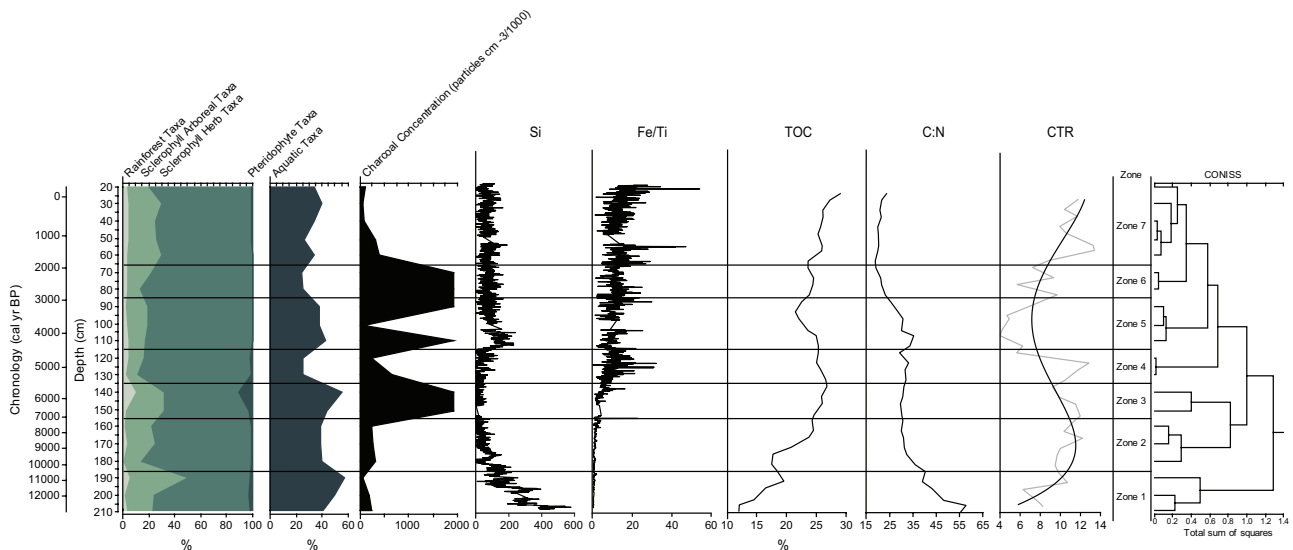


Figure 6. Summary diagram showing summary pollen, micro-charcoal, silicon (Si) and iron/titanium (Fe/Ti), total organic carbon (TOC), carbon to nitrogen ratio (C:N) and corrected transmission residuals (CTR) raw data overlain by a fourth order polynomial against CONISS zones with chronology and depth.

gradual increase (~55%), while both Asteraceae (Tubuliflorae) (~11%) and Amaranthaceae (~19%) rapidly peaked and remained high for the entire zone. Aquatics showed greatly reduced values (~25%). Micro-charcoal also showed diminished values which continued to decrease.

Zone 5: 114–85 cm; ~4500–3000 cal yr BP. Restionaceae, Cyperaceae and *Myriophyllum* showed elevated values throughout Zone 5 (~41%). Grasses peaked to their highest values in this zone (~70%), while both Asteraceae (Tubuliflorae) and Amaranthaceae decreased (0.5% and 1.8% at 101 cm, respectively), before they increased again (4.9% and 9.1% at 90 cm, respectively). While the herbs decreased, *Plantago* once again peaked (~3%). Diminished values of *Eucalyptus* (~3%) returned to the record, while Casuarinaceae slightly increased (~4%). Micro-charcoal values fluctuated during this zone. There was a sharp spike at 110 cm which decreased at 100 cm before values peaked at 90 cm and plateaued into Zone 6.

Zone 6: 84–65 cm; ~3000–1900 cal yr BP. Sclerophyll herbs dominated this zone (~82%), with the majority being grasses, whereas slightly decreased values of Asteraceae (Tubuliflorae) and Amaranthaceae occurred. Sclerophyll arboreal taxa showed decreased values and was dominated by Ericaceae (10%). Aquatics, particularly Restionaceae, once again showed decreased values (25%). Micro-charcoal values remained plateaued throughout this zone.

Zone 7: 64–20 cm; ~1900 cal yr BP to present. Grasses showed relatively high values throughout this zone (~58%), with elevated abundances at the top of the record. Asteraceae (Tubuliflorae) and Amaranthaceae remained relatively stable at ~6%, and ~8%, respectively. *Plantago* also peaked at the top of the record (~3%). An increase in sclerophyll arboreal taxa (~22%), especially Proteaceae, occurred at the top of the core. Ericaceae also showed its highest values in this zone. *Eucalyptus* and *Pandanus* once again reappear in the record, as do slightly higher values of Casuarinaceae. Restionaceae also increased to ~33%, with the slight reappearance of *Myriophyllum* at the top of the record. An increase in pteridophyte variability occurred in this zone, however in minimal values (~0.6%). The exotic taxon *Pinus* appeared at the top of the record. Micro-charcoal values

showed decreasing values from 60 to 30 cm before very slightly rising at the top of the record.

Discussion

Site formation and peatland initiation

Based upon the findings of Coaldrake (1961) and Krull et al. (2004) the Carlo Creek catchment was initially a channelled palaeo-valley floor ~20,925 cal yr BP. This was during the peak of the LGM when sea level was ~120 m below present (Williams et al., 2009), the coastline was ~60 km offshore (Ellerton et al., 2020) and the environmental conditions were cooler and drier than present (Moss et al., 2013).

Between the LGIT to early Holocene the sediment in the Carlo Creek catchment was predominantly sand, before changing to peat (Krull et al., 2004). Coaldrake (1961) suggested a transition zone between the old valley floor (dominated by sand) and the peatland, with a gradual increase in organic matter (e.g., sandy peat). The base of CCS1 is a peaty sand and shows a greater proportion of inorganic sediment (higher Ti and Si and lower TOC), which is also reflected by the Mo inc/coh scattering values (Figure 6). CTR values (a proxy for peat decomposition) are low at the base of the core indicating drier conditions. This is likely due to the initiation of the peatland which would be limited in amount of peat growth and therefore it may be that the peatland was not yet saturated with water. It is possible that the sediments deposited in the base of this core represent the initiation of a low permeability perching layer (aquitard) before the development of the perched coastal peatland. This is reflected by the water chemistry in the Rainbow Beach patterned fen complex which shows the most similarity to perched aquifer bores around Cooloolo (McDougall et al., 2017). This low permeability layer and accumulation of inorganic sediments and organic matter likely caused sufficient water and nutrient availability for *E. minus* growth, which is present during this period, and allowed for the development of a peatland through paludification. This restiad tends to grow in nutrient poor sediment (Agnew et al., 1993), like the 'Cooloolo' morphosequence, which was initially aeolian but has since undergone fluvial reworking, weathering and erosion causing well sorted and leached quartz dominated sand with relatively low topography (Ellerton et al., 2020; Patton et al., 2019).

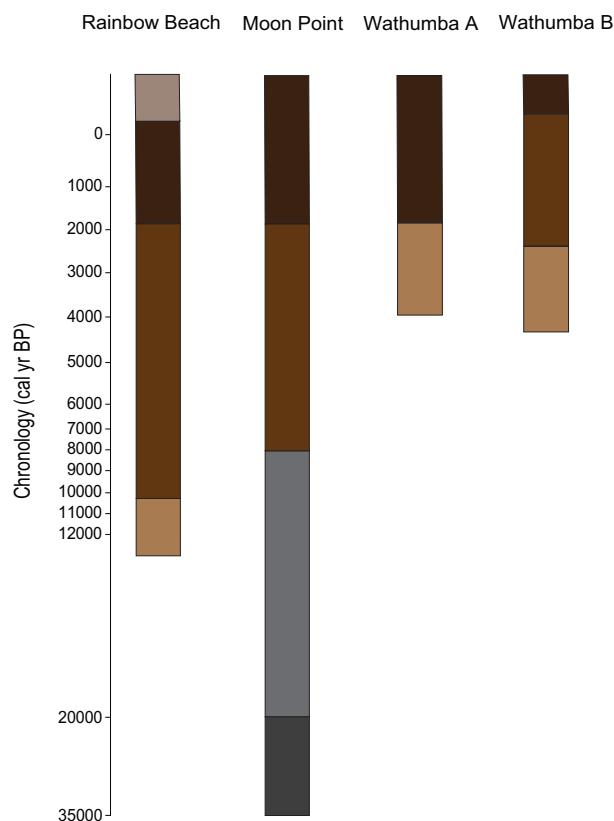


Figure 7. A comparison of cores from Rainbow Beach patterned fen complex (CCS1), K'gari (Moon Point and Wathumba cores A and B; Moss et al., 2016). Beige represents modern root mass (only found in the Rainbow Beach core), dark brown indicates fresh peat, medium brown is humified peat and light brown indicates sandy peat. Light grey represents lacustrine clay and dark grey is lacustrine silt. Chronology is based off CCS1, with the addition of Moon point's sediment contact and basal ages included.

The pollen assemblage at ~12,770 cal yr BP suggests dry conditions dominated by open eucalypt forest with an understory of grasses and daisies. The LGIT was a period with warmer and wetter conditions relative to those of the LGM, however a reversal to drier conditions in the late deglacial (~15,000–13,000 cal yr BP) has been recorded (Moss et al., 2013). Drier conditions around the late deglacial have been found at Minjerribah (North Stradbroke Island; Welsby Lagoon, Native Companion Lagoon and Tortoise Lagoon; Barr et al., 2017; Moss et al., 2013) and at K'gari (Lake Allom and Lake McKenzie; Donders et al., 2006; Woltering et al., 2014, respectively). It may be that the ameliorating climate during the LGIT provided the necessary conditions for the development of the Rainbow Beach peatland.

Mire conditions appear to stabilize between ~12,000 and 10,000 cal yr BP as indicated by the appearance of semi-emergent species *Myriophyllum* and Cyperaceae (sedges) followed by the highest peak in Restionaceae (*E. minus*) in the record. This peatland development might be conducive to patterning conditions, and therefore the initiation of the patterned fen complex; although, patterning cannot be determined through palynological analysis (Moss et al., 2016). The Moon Point mire (on K'gari) also formed during this period (Moss et al., 2016; Figure 7). Two formation processes were proposed: an infilling of a lacustrine environment and/or fluctuating climate regimes during the LGIT. The Moon Point mire was likely a deep perched lake ~35,000 cal yr BP before shallowing and becoming a mire as determined by the change in sediment. Moon Point overlies the Pleistocene aged dune morphosequence 'Awinya' (Patton et al., 2019). It may be that the antecedent topography and subsequent nutrient

availability from underlying soils, as well as distance from water sources may vary the formation processes of subtropical patterned fens.

The Wathumba peatland formed ~4300 cal yr BP directly on the sandy substrate, likely overlying the Holocene dune unit 'Triangle Cliff' on K'gari (Moss et al., 2016; Patton et al., 2019; Figure 7). The initiation of this peatland was suggested to be due to lowered sea levels after the mid-Holocene highstand (Moss et al., 2016). It is likely that a variety of factors influence subtropical patterned fen development as all three peatlands initiated via different processes.

Marine influences on the Rainbow Beach patterned fen complex

At 10,800 cal yr BP the coastal indicator taxon Casuarinaceae (due to its ability to adapt to saline conditions; Lin et al., 2017) peaked and remained high until ~5700 cal yr BP, suggesting a shift from terrestrial to coastal conditions. It is likely that as sea levels rose, the denser saline water interacted with the groundwater which influenced the expansion of the freshwater lens under the Carlo Creek catchment, moving coastal communities further inland. This is shown by the peaks in *Ophioglossum* and aquatics (primarily *E. minus* and Cyperaceae), slightly increased TOC and Mo inc/coh, decreased inorganic sediment and humification indicating wetter conditions (Figure 6). The expansion of the peatland correlates with regional sea level reaching ~1.5 m above modern sea level ~7000–5500 cal yr BP (mid-Holocene highstand) (Leonard et al., 2016, 2018). Due to this regional sea level change affecting the local freshwater lens, it appears that wetter conditions prevailed based upon increased organic matter proxies (TOC and Mo inc/coh), perhaps indicating the formation of a peat dome in the mire. Regionally, this was also a period of increased effective precipitation (Reeves et al., 2013), which has been recorded at Minjerribah (North Stradbroke Island) further south (Barr et al., 2017, 2019; Mariani et al., 2019; Moss et al., 2013). These wetter conditions correlate with a large peak in micro-charcoal concentration indicating climate variability, a peak in *Araucaria* and decreased grasses and daisy pollen found in the CCS1 pollen record (Figure 6).

Mangrove taxa (*Avicenna marina*) were found ~7000 cal yr BP at the northern end of the Carlo Creek catchment (in the current Rainbow Beach patterned fens next to the refuse centre; Moss, 2014) indicating a marine incursion. Mangroves are an indication of high intertidal zones and their pollen tend to travel very short distances (Grindrod, 1985) and were therefore likely *in-situ*. This suggests that saline water (from Carlo Creek and Tin Can Bay) was affecting the Rainbow Beach patterned fens, however, was not directly flowing over the site of CCS1 as no mangrove pollen was found in this core. This is corroborated by Köhler et al. (2021) who identified a palaeo-channel north of the Rainbow Beach patterned fen complex. Moss (2014) found a hiatus in peat deposition during the mid-Holocene highstand which may be due to marine influence. From a modern water chemistry study of various waterbodies around Cooloolo, marine influences were identified within the wet heath north of the Rainbow Beach patterned fens at an elevation of ~2.5 m (above Australian height datum) (McDougall et al., 2017).

Towards the end of the mid-Holocene highstand there was a peak in Amaranthaceae, a family of halophytes which are salt tolerant (Butler, 2017). This peak in salt marsh taxa coincides with Restionaceae (*E. minus*) showing its lowest counts throughout the record, suggesting that it does not grow as well in saline conditions (Figure 6). It is likely that this decrease in Restionaceae is indicating a contraction of the peatland due to increased saline waters.

Drier conditions follow this peatland contraction as inferred by increased humification, grass, daisy and an increasing trend in

Fe/Ti (changes in redox) and a greater ratio of inorganic (Ti, Si) to organic (TOC and Mo inc/coh) sediment (Figure 6). This correlates with many subtropical records which also record a dry phase during the middle to late Holocene, with varying timescales. Moss et al. (2013) recorded drier conditions from 5000 to 0 cal yr BP from Minjerribah, while on K'gari, Atahan et al. (2015) reported drier conditions between 6100 and 2500 cal yr BP and a hiatus in peat from Lake Allom between ~6500 to 5400 cal yr BP was attributed to drier conditions (Donders et al., 2006).

Whilst we infer a loss of surface wetness after the sea level decline around 4600 cal yr BP, there appears to be an expansion of the peatland ~4300–3200 cal yr BP, with an increase in Restionaceae, *Myriophyllum* and Cyperaceae, likely due to decreased marine influence (Figure 6). This indicates a return to conditions necessary for patterning.

Fire, climate and vegetation regimes

During the Rainbow Beach peatland development (~12,000–10,000 cal yr BP), there is a shift to slightly wetter conditions, recorded by the change to sclerophyll woodland dominated by Casuarinaceae and with decreased grasses and daisy representation, increased pteridophytes, TOC and aquatics, particularly Restionaceae (Figure 6). Micro-charcoal values are low during this period, which therefore suggests reasonably stable environmental conditions. This sclerophyll woodland broadly reflects modern terrestrial environmental conditions next to the mire. Throughout this record *Araucaria* is constantly present in small percentages, likely representing the mosaic patches of rainforest within the Cooloola Sand Mass. Increased temperature (Woltering et al., 2014) and effective precipitation (Atahan et al., 2015; Petherick et al., 2013) during the early Holocene have been recorded at Lake McKenzie, K'gari, correlating with this shift to warmer and wetter conditions.

Between ~10,000 and 9000 cal yr BP relatively drier conditions prevailed, with a peak in grasses and increased terrigenous sediment input (higher ratio of Ti and Si than TOC) and greater humification. This trend correlates with Longmore (1998) and Krull et al. (2004) who also suggested drier conditions around this time at K'gari and Cooloola, respectively.

During the mid-Holocene highstand there was a large peak in micro-charcoal which coincided with wetter conditions and a greater representation of wet sclerophyll, pteridophytes and aquatics. From the middle to late Holocene the micro-charcoal record fluctuates. The earliest archaeological site found in Cooloola is dated to ~5500 cal yr BP (McNiven, 1991), and this fluctuating record may imply a change to a landscape that is managed by Indigenous burning practices. There are limited archaeological investigations of the region, and therefore, it may mean that the landscape was managed by Indigenous peoples much earlier than this.

From ~4200 cal yr BP the surrounding landscape was dominated by open sclerophyll woodland and herbland, which was indicated by the reappearance of fire tolerant *Eucalyptus* and *Plantago* (an indicator taxon for disturbance) and increase in grass. During this period peaks in Cyperaceae, *Myriophyllum* and Restionaceae indicate conditions conducive for patterning. This is approximately around the time when the Wathumba patterned fen complex on K'gari formed (~4300 cal yr BP; Moss et al., 2016). This suggests that *E. minus* peatlands prefer more open landscapes.

Micro-charcoal peaks abruptly at ~4200 cal yr BP, which correlates with macro-charcoal presence found within the patterned fen complex (indicating a local fire rather than regional climate variability) (Moss, 2014). This may be an indication of local Indigenous land management as other lakes on K'gari (Lake Allom and Lake McKenzie; Atahan et al., 2015; Donders et al.,

2006), and Minjerribah (Blue Lake, Tortoise Lagoon and Welsby Lagoon; Barr et al., 2013; Moss et al., 2013) do not record this micro-charcoal peak.

Between ~3200 and 2100 cal yr BP a peak in micro-charcoal occurred. This correlates with an increase in climate variability due to changes in ENSO frequency after ~4000 cal yr BP (Barr et al., 2019; Donders et al., 2006; Shulmeister and Lees, 1995).

Around 3200 cal yr BP Amaranthaceae and Asteraceae (Tubuliflorae) reappear and remain relatively consistent with slight fluctuations for the rest of the record. This coincides with a slight peak in Fe/Ti and increased humification which may be indicating locally drier conditions (Figure 6). Restionaceae also slightly decreases (between ~2700 and 2100 cal yr BP), as does peat production (i.e., lower Mo inc/coh and TOC) ~2700 cal yr BP. These local conditions correlate with drier conditions inferred from records on Minjerribah (Barr et al., 2017; Mariani et al., 2019; Moss et al., 2013) and also at K'gari (Hembrow et al., 2018).

From ~1600 cal yr BP to present, environmental conditions appear relatively stable with the exception of increased variability in sclerophyll arboreal taxa (Figure 6). Restionaceae (*E. minus*) returns to higher percentages which correlates with a large increase in fen taxa Ericaceae. There is a general increase in peat production (Mo inc/coh, TOC), while humification decreases, indicating generally wetter surface conditions (Figure 6). As this is located in the acrotelm, this signal may not reliably represent wetter conditions as the peat has not had time to break down and humify (Chambers et al., 2011).

European impact on fire regimes

European colonial occupation occurred in Cooloola during the 1860s (McNiven, 1991), where Kauri pine (*Agathis australis*) logging occurred. The exotic taxon *Pinus* appeared at the top of the record which is commonly used as an indicator of European settlement (Donders et al., 2006; Haberle et al., 2006). During the late Holocene micro-charcoal values are extremely low relative to the rest of the record, reflecting decreased fire regimes from post-European fire suppression. This trend has been recorded around Australia (Hanson et al., 2022; Moss et al., 2011, 2015). Once again there is a shift in fire regimes towards more fire tolerant *Eucalyptus* at the top of the record. Regionally, there appears to be an opening up of the landscape (indicated by increased grasses, *Pandanus*, *Plantago* and Ericaceae), while locally, vegetation thickening from post-European fire suppression appears to be occurring at the top of CCS1, as shown by the increase in sclerophyllous shrubland (e.g., *Melaleuca* and Proteaceae (Lomatia, *Hakea* etc.)). This suggests that the Rainbow Beach patterned fen complex in the Carlo Creek catchment may require frequent burning to remove encroaching vegetation from the complex. It has been suggested that the patterned fen complexes on K'gari are resistant to fires within the peatland (due to the *E. minus* root system protecting the underlying peat from combustion) with the major site impacts being a reduction of advancing shrubs (Fairfax et al., 2011; Moss et al., 2016). In a recent study, Stewart et al. (2020) indicated that the K'gari patterned fen complexes are also under threat from vegetation thickening.

Conclusion

The Rainbow Beach patterned fens are a complex system situated nearby to townships and are potentially affected by pollution from the nearby refuse centre, weed invasion and also animal pest species (Moss, 2014). These patterned fens are a GDE which appear to show greater sensitivity to variations in sea level, salinity and also climate than those on K'gari. The Rainbow Beach peatland initiated ~12,770 cal yr BP, forming a semi-perched layer (aquitard). This caused conditions conducive for *E. minus* peatland

development, with possible patterning between 12,000 and 10,000 cal yr BP. This fen formation differs from that of Moon Point (on K'gari) which initially was a perched lake ~35,000 cal yr BP that underwent infilling and shifted to mire conditions ~12,000 cal yr BP, with possible patterning. It is likely that the Rainbow Beach patterned fens initiated due to the ameliorating climate conditions during the LGIT. It may be that the antecedent topography and underlying soils and also distance from the coastline also impact subtropical patterned fen formation. The Moon Point patterned fens have remained relatively stable since mire formation, and have been suggested to be resilient to wildfires, changes in sea level and also hydrology. However, the Rainbow Beach complex was affected by rising sea levels during the early Holocene, causing paludification of the peatland which moved coastal communities inland and may have raised the freshwater lens therefore expanding the mire. Increased salt marsh taxa correlated with decreased *E. minus* growth which suggests that *E. minus* does not favour saline conditions. Therefore, with rising sea levels causing increased saline water within the Rainbow Beach patterned fen complex, *E. minus* growth will likely be under pressure. Further fen development or patterning occurred ~4200 cal yr BP, roughly coinciding with the formation of the Wathumba complex which was suggested to form due to lowered sea levels and relatively increased freshwater supply (Moss et al., 2016). The Rainbow Beach patterned fen record suggests increased vegetation thickening due to post-European fire suppression, which has also been found to occur at Moon Point (Stewart et al., 2020). The patterned fen complexes on Cooloola and K'gari show different formation processes, likely due to a combination of hydrology and geomorphology of the complexes, and also resilience to different external processes. As such, subtropical patterned fen complexes should be assessed on an individual basis to identify local sensitivities and peatland trajectories.

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ORCID iD

Johanna M Hanson  <https://orcid.org/0000-0001-8204-862X>

Supplemental material

Supplemental material for this article is available online.

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