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Late Quaternary Vegetation History of North Stradbroke Island, Queensland, Eastern Australia

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Abstract

Currently there is a paucity of records of late Quaternary palaeoenvironmental variability available from the subtropics of Australia. The three continuous palaeoecological records presented here, from North Stradbroke Island, subtropical Queensland, assist in bridging this large spatial gap in the current state of knowledge. The dominance of arboreal taxa in the pollen records throughout the past >40,000 years is in contrast with the majority records from temperate Australia, and indicates a positive moisture balance for North Stradbroke Island. The charcoal records show considerable inter-site variability indicating the importance of local-scale events on individual records, and highlighting the caution that needs to be applied when interpreting a single site as a regional record. The variability in the burning regimes is interpreted as being influenced by both climatic and human factors. Despite this inter-site variability, broad environmental trends are identifiable, with changes in the three records comparable with the OZ-INTIMATE Climate Event Stratigraphy.

Highlights

- Three continuous palaeoecological records that extend beyond the last glacial maximum are examined for the first time from the subtropics of eastern Australia.
- Presence of continuous records and dominance of arboreal taxa indicates a positive moisture balance for the last +40,000 years for North Stradbroke Island.
- Substantial spatial variability is observed in the pollen and charcoal records that suggest that site specific variability may greatly influence burning regimes and pollen representation.
- Changes in North Stradbroke Island vegetation strongly influenced by widely observed Australian climate regimes during the Late Quaternary.

- Changes in burning regimes on North Stradbroke Island are influenced by a combination of climatic and human factors.

Keywords

Late Quaternary climate dynamics, subtropical Queensland, last glacial maximum, Australia, pollen, charcoal, lake sediments

1. Introduction

There is a relative paucity of continuous high temporal resolution palaeo-environmental records (terrestrial, palaeoecological and lacustrine) in the subtropics of eastern Australia extending to, and beyond, the last glacial maximum (LGM), as defined by maximum sea level lowering between 22,000 and 19,000 calendar years Before Present (cal yr BP) (Yokoyama et al., 2000). The subtropics are defined here under the Köppen classification, which itself is based on the premise that native vegetation is the best indicator for climate zones (Köppen, 1931). Stern et al. (2000) later described Australian biomes more specifically by developing subcategories to Köppen's original scheme. Focusing on southeast Queensland, North Stradbroke Island (NSI) is situated in the subtropical zone [i.e. mean annual temperature >18^{o}C with a distinctly dry winter (Stern et al., 2000)], close to the border with the temperate zone to the south (see Figure 1). As outlined by the reviews of Hope et al. (2004), Turney et al. (2006), Williams et al. (2009), Reeves et al. (this volume a and b) and Petherick et al. (this volume), most continuous records in Australia extending beyond the LGM have been developed from the northern Wet Tropics of eastern Australia, temperate New South Wales, Victoria, eastern South Australia and western Tasmania. The bulk of these studies focus on the results from a single site and hence there is a challenge in discerning inter from intra site variability.

Within the subtropical region there are only four records that extend beyond the LGM, including the continuous >40,000 cal yr BP (calibrated years Before Present) Native Companion Lagoon (NCL) record from North Stradbroke Island (NSI) (McGowan et al., 2008; Petherick et al., 2008a, 2008b); the 18,600 ^{14}C yr BP (radiocarbon years Before Present) at Tin Can Bay swamp, Rainbow Beach, Cooloola (Krull et al., 2004); the 56,000 ^{14}C yr BP Lake Allom record from Fraser Island, which has a hiatus between 28,000 to 10,000 ^{14}C yr BP (Longmore, 1997; Donders et al., 2006); and the 600,000 year old Lake Coomboo record from Fraser Island, which is thought to be subject to significant dating errors that poorly constrain the LGM, as well as containing a hiatus in sedimentation from 21,800 to 12,160 14C yr BP (Longmore and Heijnis, 1999). The scarcity of records from subtropical Australia results in a significant gap in knowledge of understanding of late Quaternary climate variability for Australia in particular, and for the Southern Hemisphere in general. This is because the subtropics are an important 'link' between the tropics and temperate climate regions and as such, records from these locations have the potential to demonstrate responses to a variety of climatic forcings operating over a range of temporal and spatial scales. Furthermore, the responsiveness of regional climate and dependent ecosystems to global climatic forcings is a matter of some uncertainty. Hence, records of past responses at regional scales can significantly enhance understanding of climate variability and environmental change.

In this study, three continuous pollen and charcoal records that extend beyond the LGM are presented from NSI, eastern Australia (Figure 1). These are compared with the OZ-INTIMATE Climate Event Stratigraphy (CES) for the Australian region (Reeves et al., this volume a) and the review, undertaken by Petherick et al. (this volume), of palaeoclimatic records for the last 30 ky from temperate Australia to compare and contrast environmental responses to key drivers of subtropical climate variability that influenced the Australian continent during the late Quaternary period. Preliminary results have been presented from one of these records, NCL, by McGowan et al. (2008) and Petherick et al. (2008a, 2008b), however these studies primarily focused on the late Quaternary dust flux and only provided a broad overview of the pollen and charcoal records. Pollen and charcoal data are documented for the first time from Tortoise Lagoon (TOR) and Welsby Lagoon (WEL) from North Stradbroke Island also and, in combination with the NCL record, provide the first record of environmental change for this coastal subtropical site. This combination of similar aged palaeo-records from a relatively small area provides a unique opportunity to investigate intra and inter site variability, allowing the impacts of site specific factors on proxies that are used to develop regional environmental reconstructions to be investigated.

2. Regional Climatic Dynamics

In terms of contemporary climate dynamics the subtropical region of eastern Australia (incorporating southeast Queensland and northeast New South Wales) is characterised by a wet summer (300 – 400 mm) and relatively low rainfall winter (100 – 130 mm) (Australian Bureau of Meteorology (BOM), 2005). This summer dominant rainfall regime results from the poleward migration of the Inter-Tropical Convergence Zone (ITCZ) in response to the Southern Hemisphere solar maxima and the delivery of rain by warm humid maritime air masses and associated synoptic circulation systems. This is in marked contrast with the southern temperate zone (incorporating southern New South Wales, eastern Victoria and Tasmania), which derive most of their precipitation in winter from the passage of low pressure systems and associated cold fronts (BOM, 2005). The other significant weather system that influences in south-east Queensland is the rain-bearing East Coast Lows, which may significantly increase winter precipitation (Hopkins and Holland, 1997; BOM, 2007).

There are a number of modern drivers of climatic variability that influence precipitation within the subtropical region. These include the El Niño/Southern Oscillation (ENSO) phenomenon, which is linked to alterations in ocean temperatures and pressure gradients across the Indo-Pacific region (Risbey et al., 2003), the Pacific Decadal Oscillation (PDO) and the Southern Annular Mode (SAM)/Antarctic Oscillation (AAO).

The El Niño phase is associated with warmer ocean temperatures across the central and eastern Pacific Ocean and above average mean sea level barometric pressure over the Indonesian-North Australian region, while the central Pacific experiences below average pressure. The key impact of this is a weakening of the rain-bearing southeast trade winds resulting in lower than average rainfall (Manins et al., 2001; Hill et al., 2009) that may result in major drought events in eastern Australia (Risbey et al. 2003). In contrast, La Niña events result in anomalously high rainfall across the subtropical region. ENSO operates over a number of timescales, from inter-annual (e.g. 2 to 7 year) variability to millennial (e.g. 2000 year) and semi-precessional timescales (e.g. 11.9 ky) (Heusser and Sirocko, 1997; Clement et al., 2001; Tudhope et al., 2001; Moy et al., 2002; Crimp and Day, 2003; Turney et al., 2004). There is also evidence from a number of records that an increase in ENSO amplitude and intensity (to modern conditions) has occurred after the mid-Holocene period (e.g. McGlone et al., 1992; Shulmeister and Lees, 1995; Moy et al., 2002; Gagan et al., 2004; McGowan et al 2012).

The PDO is a decadal-scale oscillation of sea surface temperatures in the North Pacific that has a significant influence on Australian rainfall (Mantua and Hare, 2002; McGowan et al., 2009). There are two PDO phases, with the “warm” mode associated with below average rainfall and the “cool” phase linked to above average rainfall within Australia (Crimp and Day, 2003; McGowan et al., 2009). Around 25 to 44% of modern summer rainfall variability within Queensland is attributed to interactions between the PDO and ENSO (Crimp and Day, 2003). McGowan et al. (2010) have identified a link between hydroclimatic variability and the PDO for the Snowy Mountains region of south-eastern Australia for the last 6,500 years, which suggests that this oscillation may have increased aridity through modulation of ENSO for some of this time period.

The mid-latitude westerly winds are a key feature of the meteorology of the Southern Hemisphere in the mid to high latitudes (Garreaud et al., 2009), with depressions and rain bearing troughs playing an important role in the climate of Australia (Pitman et al., 2004), particularly with southern Australian winter rainfall regimes (BOM, 2005). In addition, cold fronts embedded within the circumpolar westerly flow can play a major influence on landscape dynamics as they travel north over Australia through wind erosion and the transport of surface sediments (Hess and McTainsh, 1999). In particular, Petherick et al. (2008a) have linked the occurrence of two dry stadial periods during the LGM with a dominant pattern for the subtropics of eastern Australian suggesting the northward drift of the mid-latitude westerlies. The SAM/AAO is the main driver of the inter-annual phase of the westerlies, with a negative SAM/AAO associated with the northward movement and a positive SAM/AAO linked to a southward shift. This movement has been significantly correlated with precipitation in southern temperate Australia (Hendon et al., 2007) and

SAM/AAO is also modulated by interactions with ENSO, with the amplification of climate effects linked to complimentary trends in each phenomenon (Fogt and Bromwhich, 2006).

3. Site Description

North Stradbroke Island is the second largest sand island in the World and forms the eastern side of Moreton Bay in southeast Queensland, Australia. The Pleistocene-Holocene parabolic dune systems that form the island were created by aeolian movement of sand, largely during glacial periods by the dominant south-easterly trade winds (Ward, 2006). The parabolic dune form results from destabilisation (i.e. loss of vegetation cover) of an area of the dune field which is otherwise vegetated and stable. These dunes are generally between 100 and 150 m high, with the highest point of the island being Mt Hardgrave (239 m above sea level). The island is 32 km long in a north-south direction, with a maximum width of around 11 km at its northern end, and covers an area of around 285 km^2 in a roughly triangular shape (Figure 1).

Vegetation of the island consists predominantly of a mixture of dry sclerophyll forest, woodland and heath communities, with mangroves occupying the sheltered western (Moreton Bay) side of the island and a small patch of rainforest located at Myora Springs (Figure 1) (Clifford and Specht, 1979; Moss et al., 2011). The dominant vegetation on NSI reflects dune age (i.e. follows a retrogressive succession process) with coastal closed forest/scrub found on the youngest Holocene dunes, eucalypt open forest on the intermediate Pleistocene aged dunes and eucalypt woodland and wallum heath on the oldest Pleistocene dunes (Clifford and Specht, 1979; Thompson, 1981; Walker et al., 1981).

The unconfined aquifer of NSI is an important water resource, with groundwater extracted to supply water for mining operations on the island and domestic water supply both on the island and the mainland with current extraction rates estimated at 20.6 GL yr^{-1} (Leach, 2011). This substantial groundwater resource results from the geomorphology of the island, with the sand regolith allowing easy infiltration of rainwater and the volcanic/sandstone bedrock assisting in the retention of a large freshwater lens and the resultant groundwater mound (Bedford, 2006). The large volume of water within the island supports numerous freshwater springs (e.g. Myora Springs and Eighteen Mile Swamp) and window lakes (e.g. Blue Lake) with these lakes (i.e. depressions) and springs (i.e. on the island edges) occurring at the interface of the island's water table. Numerous perched wetlands (e.g. Brown Lake, Native Companion Lagoon, Tortoise Lagoon and Welsby Lagoon) also occur and are formed in depressions where an impermeable layer has formed in the soils near the surface, preventing water from percolating to the water-table. These layers are the result of chemical reactions between soil and water that precipitate organic and inorganic matter in the soil profile (Timms, 1986). The wetlands located on NSI provide excellent natural archives to reconstruct different aspects of past environmental conditions through a variety of palaeo-environmental proxies. In particular, these records provide the ability to assess the relative impacts of late Quaternary climate variability and human impacts on the island, as well as the broader subtropical environments of eastern Australia.

Archaeological evidence for human occupation and island exploitation comes primarily from the Wallen-Wallen Creek site on the island's west coast which indicates continuous occupation for at least the last 20,000 ^{14}C yr (Neal and Stock, 1986). This study also suggested a possible intensification of occupation with a greater density of artefacts and archaeological charcoal found in the late Holocene deposits of this site. The main Aboriginal impact on NSI was linked to hunter-gather activities, although fire may have been used to shape the local vegetation communities of the island (Clifford and Specht, 1979; Moss et al., 2011). European settlement of NSI dates to 1827 when Dunwich was established as a convict settlement. Farming was attempted on the island (cotton farming was reported at Myora in 1828) but was abandoned. Major economic activity on the island is now related to tourism and sand mining (which began in the 1950s) for rutile, zircon and glass sand. Around two-thirds of NSI is currently leased for sand-mining. More recently, a plantation of slash pine (*Pinus elliotii*) was established near Brown Lake in the 1960s (Clifford and Specht, 1979). A key impact of European colonisation appears to be a change in fire regimes, which favoured the expansion of Myrtaceae taxa at the expense of the Casuarinaceae, as well as an expansion in weed taxa and grasslands (Moss et al., 2011).

The island experiences warm, moist summers (~29°C) with mild winters (~14°C). Rainfall is summer dominated (i.e. November to April) and average annual rainfall is between 1500 (west coast) to 1700 mm (east coast) per year. During the winter months, winds are predominantly from the southwest and in summer (the period of strongest winds), the easterly quarter (BOM, 2012a; 2012b).

The three study sites presented here are located in different parts of NSI, with NCL situated in the southwest (Moreton Bay side) of island at 27° 40’ 33” S, 153° 24’ 37” E and 27 m above sea level (m.a.s.l).; TOR is located within the high dunes of the island on the northeast (Coral Sea side) of the island at 27° 30’ 59” S, 153° 28’ 27” E and 39 m.a.s.l; and WEL is situated near the northwest coast at 27° 26’ 12” S, 153° 26’ 56” E and 29 m.a.s.l (Figure 1). NCL is an ephemeral perched lake system with sedges and reeds growing along the lakeshore, which may spread to the lake bed when dry, and is located within the mining lease. The site is surrounded by eucalypt dominated sclerophyll woodland with coastal mangroves within 1.3 km of the site on the Moreton Bay shore. TOR is an ephemeral perched lake in a dune swale between two +130 m dune crests situated within the Blue Lake National Park. The vegetation on the surface of the lagoon currently consists of sedges and reeds. The surrounding vegetation is dominated by eucalypt forest with a grass and heath understorey, and there is a significant area of Casuarinaceae forest along the northern edge of the lagoon. WEL currently (2012) has a water depth of between 0.5 to 1 m and is also dominated by sedges and reeds, with significant patches of *Melaleuca* within and fringing the lagoon. The surrounding vegetation consists of eucalypt forest and woodlands and Casuarinaceae woodlands, with a predominantly heath understorey.

4. Methods

One core was collected from each site using a Russian D-section corer, with a 3.88 m core collected from NCL (Figure 2); a 5.01 m core from TOR (Figure 3); and a 4.50 m core from WEL (Figure 4). The NCL and TOR cores were stored and sub-sampled at the School of Geography, Planning and Environmental Management, The University of Queensland, while the WEL core was stored and sub-sampled at Geography, Environment and Population, The University of Adelaide. Each core has been sampled at different increments for pollen and charcoal analysis, NCL at an average of 400 year time intervals (every 5 cm); TOR at an average of 660 year time intervals (every 10 cm); and WEL at around 295 year time intervals (every 5 cm) from 51 to 120 cm, and then an average of 655 year time intervals (every 10 cm) for the remainder of the core.

Pollen samples were prepared for analysis using the technique developed by van der Kaars (1991). This involved using sodium pyrophosphate to disaggregate the sediments which were then further processed by using sodium polytungstate (specific gravity of 2.0) to float the lighter organic fraction from the heavier minerogenic component. The samples then underwent acetolysis to darken the pollen grains and aid their visibility under a light microscope. All samples were mounted in glycerol, with pollen identification and counting undertaken using a light microscope at x400 magnification. The pollen sum consisted of a minimum of 300 dryland pollen grains or two completely counted slides. Charcoal analysis involved counting all black angular particles > 5 μm in size across three evenly spaced transects at all depths using a light microscope at x400 magnification (Wang et al., 1999). Pollen and charcoal concentrations were determined from counts of exotic *Lycopodium* marker grains, which were added as a tablet with a known *Lycopodium* concentration at the start of the pollen analysis (Stockmarr, 1971; Wang et al., 1999). Table 2 shows all of the pollen taxa found in each record, along with the family affinities and plant habitat with each of the pollen taxa for the three sites. A summary pollen diagram, which does not include taxa with low values (less than 2.5 %) was created for the three records. The summary pollen diagrams were produced using TGView (Grimm, 2004) and were divided into zones based on the results of a stratigraphically constrained classification undertaken by CONISS (Constrained Incremental Sums of Squares cluster analysis; Grimm 1987, 2004) on taxa contained within the pollen sum (see table 2).

In order to summarise the main patterns of change in the terrestrial vegetation, Principal Components Analysis (PCA) of terrestrial pollen data (i.e. taxa in the pollen sum) was undertaken in CANOCO for Windows 4.53 (ter Braak and Šmilauer, 2002). PCA was chosen as the most appropriate ordination method as the gradient length of main variation in the data (as determined using Detrended Correspondence Analysis with detrending by segments) was less than two (Lepš and Šmilauer, 2003). PCA was undertaken on a variance-covariance matrix. As a result of the strong influence that the small number of samples with abundant

Monotoca and *Hydrocotyle* pollen had on the PCA from Tortoise Lagoon, these taxa were down weighted in the ordination from this site.

Eighteen peat samples were radiocarbon dated from the NCL core at The University of Waikato (refer to Petherick et al. 2008a). For the TOR record, seven organic and five pollen concentrate samples were ^{14}C dated at the ANTARES facility, Australian Nuclear Science and Technology Organisation. Results indicated contamination of the pollen concentrates, with all five returning erroneously young ages. In addition, sample TOR-D-007, which returned an age of 16,870 ^{14}C yr (at a depth of 470.5 cm), has also been discounted as too young. In the WEL core, the Holocene ages consistently increase with increasing depth. However in the deeper sediments, a mix of pollen and peat samples indicate younger sediment ages, while a mix of three samples (pollen, peat and charcoal) is indicative of older deposition (Table 1). Given that charcoal, which is resistant to degradation, often returns old ages (Björck and Wohlfarth 2001), we excluded the older series of dates from our analysis (see Table 1). After exclusion of outlying ages (from TOR and WEL) Bayesian age modelling in OXCAL 4.1 (Bronk Ramsey 2009) was used to estimate the ages of the three profiles using Bronk Ramsey's (2008) depositional model approach and the IntCal09 (Reimer et al. 2009) calibration curve. To account for the differences between radiocarbon ages between the Northern and Southern Hemispheres, 44 years was added to the ^{14}C age and 7 years (see Hogg et al., 2011) to the standard error before ages were calibrated.

5. Results

The summary pollen and charcoal results are discussed for each record in detail below based on stratigraphic classification that has separated the results into pollen taxa zones. Also included in each pollen diagram is the lithology for each of the sites. Table 2 shows all of the taxa present at the three sites along with the family affinities and plant habitat for each of the pollen taxa. There are a total of 66 pollen taxa in the NCL record, and 50 and 54 total pollen taxa in the TOR and WEL records respectively. Figure 5 displays the results of a PCA on the pollen sum taxa for the three records to examine environmental variability, and also illustrates key pollen taxa with ages for the three sites, which was used to establish a regional chronology for NSI for the late Quaternary period.

Native Companion Lagoon (NCL) (Figure 2)

The NCL record consists almost entirely of dark-organic rich peats that become progressively sandier as the base of the core is reached (from 350 to 388 cm). The age-depth model indicates the record spans more than 47,000 years. The NCL pollen record is dominated by sclerophyll arboreal taxa, with Casuarinaceae and eucalypts being the most abundant taxa. Rainforest pollen, predominantly from *Araucaria*, maintains relatively high values from 388 to 176 cm (~47,000 to 19,600 cal yr BP) and then sharply decline from this point, while sclerophyll herbs, particularly Poaceae, have a consistent representation throughout the record with higher values from 350 to 100 cm (42,500 to 13,700 cal yr BP). Aquatics, ferns and mangroves are a relatively minor component of the pollen flora. The key aquatic taxa are *Melaleuca*, Cyperaceae, Restionaceae, which declines towards the top of the record, and *Myriophyllum*. Pteridophytes are a minor component of the record and are more abundant with the higher values of rainforest taxa from 388 to 176 cm. Mangroves consist predominantly of *Avicennia marina, Rhizophora stylosa, Ceriops tagal* and *Bruguiera gymnorrhiza*, which become apparent in the top of the record (~75 cm; ~9,600 cal yr BP). The classification of pollen undertaken on the core identified six zones.

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NCL A (388 to 350 cm; ~47,130 to 42,500 cal yr BP)

NCL A is dominated by Casuarinaceae (~46 to 67% of the dryland pollen sum), with eucalypts being the next most important taxon (~9 to 17%). Myrtaceous shrubs (generally *Baeckia*, *Tristania* and *Leptospermum*) maintain relatively low but consistent values throughout this zone and the rest of the record. Rainforest taxa, mainly *Araucaria,* make up ~more than 10% of the dryland pollen sum in most samples, while sclerophyllous herbs, mainly Poaceae and Asteraceae (Tubuliflorae), are a relatively minor component (less than 17%). In terms of the wetland taxa, aquatics, mainly *Melaleuca*, Cyperceae and Restionaceae, and pteridophytes (monolete fern spores), maintain relatively low values (less than 15% and 5% of the total pollen sum respectively). Charcoal values have some of their largest peaks in the record at 388 cm (~42,130 cal yr BP) and 363 cm (~44,100 cal yr BP).

NCL B (350 to 252 cm; ~42,500 to 31,100 cal yr BP)

A sharp decline in Casuarinaceae (from ~47 to 22%) is observed in this zone, with corresponding increases in sclerophyll herbs (from ~13 to 26%), particularly Poaceae, Asteraceae (Tubuliflorae), *Tubulifloridites pleistocenicus* (which decline at 300 cm; ~37,600 cal yr BP) and chenopods, and eucalypt values slightly increase (generally to above 20%). Rainforest taxa maintain consistent values with the previous zone until 300 cm (~37,600 cal yr BP), when there is an increase in *Araucaria* and palms that is also associated with a peak in *Callitris* values. Generally, there is an increase in aquatic taxon abundances, particularly *Melaleuca*, and an increase in fern representation from around 300 cm (~37,600 cal yr BP). Charcoal values are generally lower in this zone, except for a peak at 348 cm (~42,300 cal yr BP) and from 265 to 275 cm (~33,100 to 34,600 cal yr BP).

NCL C (252 to 176 cm; ~31,100 to 19,600 cal yr BP)

Casuarinaceae values increase in this zone (generally to ~40 to 70%), which corresponds to a decline in rainforest taxa and eucalypts from 250 to 199 cm, which then increase for the remainder of the zone. *Dacrydium guillauminii* has its last occurrence in the record at 193 cm (~22,200 cal yr BP). In addition, *Monotoca* abundances increase to around 5%, while *Dodonaea* representation declines and these values are maintained throughout the rest of the record. Sclerophyll herbs maintain consistent values with the previous zone, but there is a change in the pollen composition, with a sharp increase in Poaceae representation and a corresponding decline, which is maintained for the rest of the record, in Asteraceae (Tubuliflorae) abundances. There is an initial decline in aquatic representation, except for a small peak in *Myriophyllum* from 232 to 250 cm (~28,000 to 30,800 cal yr BP), which is followed by an increase in *Melaleuca* and Restionaceae abundances from 199 cm (~23,200 cal yr BP). Pteridophytes maintain consistent values with the previous zone. Charcoal values are generally low for this zone, except from a peak from 193 to 179 cm (between 22,200 to 20,100 cal yr BP).

NCL D (176 to 71 cm; ~19,600 to 9,600 cal yr BP)

There is an increase in Casuarinaceae abundances (consistently above ~50%) and a decline in rainforest representation. Eucalypt values initially decline (below ~15%) and then increase (above ~15%) at 117 cm (14,800 cal yr BP) in this zone. *Banksia* representation increases in this zone from 131 cm (~16,100 cal yr BP), while sclerophyll herb abundances, mainly Poaceae, initially increase (to above 15%) from 175 to 110 cm (~19,600 to 13,700 cal yr BP) and then decrease (to below 15%) for the remainder of the record. The last appearance of *Tubulifloridites pleistocenicus* in the record occurs at 85 cm (~11,000 cal yr BP). There is a decline in aquatic and pteridophyte abundances, except for a peak in Cyperaceae and Restionaceae values at 110 cm (~13,700 cal yr BP). Charcoal values are generally low in this zone, except for two peaks at 110 cm (~13,700 cal yr BP) and 80 cm (~10,500 cal yr BP).

NCL E (71 to 12 cm; ~9,000 to 1,250 cal yr BP*)*

In NCL E, Casuarinaceae obtain their highest abundances (between 58 to 80%), while there is relatively low representation of rainforest and sclerophyll herbs in this zone. Mangroves make their first appearance, and aquatics, apart from small peaks in *Myriophyllum*, as well as pteridophytes maintain low values. Charcoal abundances are initially very low in this zone but sharply increase from 34 cm (~5,600 cal yr BP), with elevated values for the remainder of the record.

NCL F (11 to 0 cm; ~1,250 to 0 cal yr BP*)*

In zone NCL F there is a slight decrease (to ~60%) in Casuarinaceae representation and a corresponding increase in eucalypts. Rainforest taxa are almost non-existent in the zone and there is a slight increase in Poaceae values. Charcoal abundances maintain sustained high values throughout this zone.

Tortoise Lagoon (TOR) (Figure 3)

The Tortoise Lagoon core consists of alternating peat and lacustrine muds which are shown in the lithology section of the pollen diagram. A total of twelve samples have been AMS radiocarbon dated (seven based on bulk organic sediments and five based on pollen concentrate) and the total length of the core covers a continuous period of 37,000 years. The TOR pollen record is dominated by sclerophyll arboreal taxa, although there is a greater abundance of sclerophyll herbs from 501 to 172 cm (~37,000 to 11,800 cal yr BP), particularly Poaceae and *Hydrocotyle* (which peaks at 11,800 cal yr BP), than in the NCL record. Eucalypts and *Monotoca* are the other key sclerophyll arboreal taxa, while rainforest, predominantly *Araucaria*, have lower abundances than in the NCL record. Mangroves are absent from this record and pteridophytes comprise a relatively minor component of the total pollen sum. Aquatics are more important in this record than in NCL and the key aquatic taxa are *Melaleuca* and Restionaceae, while sedges have much lower abundances than these two taxa. The classification of the pollen record identified six zones.

TOR A (501 to 405 cm; ~37,000 to 29,500 cal yr BP)

Casuarinaceae dominates this zone with values around 38 to 62% of the pollen sum, while eucalypts and grasses are the next most important component of the dryland pollen sum. There is a small peak in Protaceae values (i.e. *Lomatia*, *Hakea* and *Persoonia*) and Myrtaceous shrubs (i.e. *Baeckia, Tristania* and *Leptospermum*), which peak towards the top of the zone, while *Callitris* and *Monotoca* maintains small but consistent abundances in this zone. *Melaleuca* is the dominant wetland taxon, with low but consistent values of Cyperaceae and Restionaceae. Charcoal particle abundances are very low in this zone.

TOR B (405 to 282 cm; ~29,500 to 18,500 cal yr BP)

This zone has a great deal of variability in Casuarinaceae and grass representation, as well as increased representation of *Araucaria* (which declines towards the top of the zone), Restionaceae and Cyperaceae, while lower eucalypt and *Melaleuca* abundances also occur. Casuarinaceae values sharply decline (to less than 25%) at 401 cm (~29,200 cal yr BP) and at 258 cm (~16,200 cal yr BP) and there is an associated increase in Poaceae representation. Between these two depths Casuarinaceae abundances are higher (above 40%) and there is a peak centred on 372 cm (~26,900 cal yr BP), which is also associated with three small peaks in *Callitris,* while the reverse pattern is observed with grass representation. *Monotoca* and myrtaceous shrubs decline and there is a peak in Asteraceae (Tubuliflorae) values at 401 cm (29,200 cal yr BP) and *Tubulifloridites pleistocenicus* abundances from 296 to 306 cm (~20,200 to 21,400 cal yr BP). The last occurrence of *Dacrydium guillauminii* is observed during this zone at 287 cm (~19,000 cal yr BP) and charcoal particles maintain low values throughout the zone.

TOR C (282 to 167 cm; ~18,500 to 11,400 cal yr BP)

Members of the Myrtaceae family (*Eucalyptus*, Myrtaceous shrubs and *Melaleuca*) are the dominant taxa found within this zone. Casuarinaceae are still very important but have their lowest average values in the record (~19 to 46%), while rainforest taxa, grasses, Asteraceae (Tubuliflorae) and *Tubulifloridites pleistocenicus* [last appearance at 210 cm (~13,900 cal yr BP)] markedly decline. *Monotoca* abundances increase in this zone and small peaks in *Callitris*, *Dodonaea*, *Banksia*, *Acacia* are also observed, while Restionaceae abundances initially decline and then increase in this zone. At 172 cm (11,800 cal yr BP) the herb taxa *Hydrocotyle* almost complete dominates the record (90% of the pollen sum), with virtually all other taxa maintaining markedly lower representation. Charcoal particle abundances obtain their highest representation in the record, with the largest peak at 258 cm (~16,200 cal yr BP) and generally higher values across the whole zone.

TOR D (167 to 158 cm; ~11,400 to 10,600 cal yr BP*)*

This zone observes the almost complete dominance of *Monotoca*, with virtually all other taxa maintaining markedly lower representation (below 30%). Charcoal particle values have low representation in this zone.

TOR E (158 to 5 cm; ~10,600 to 400 cal yr BP*)*

Casuarinaceae values sharply increase in this zone and maintain their highest representation in the record at between 54 to 82%, while eucalypt values also increase. *Monotoca* values markedly decline to less than 10% of the pollen sum and Poaceae values recover to approximately 5%. There are small peaks in *Callitris, Banksia* and *Acacia*, while there is also higher representation of rainforest (mainly *Araucaria*) and pteridophytes. The dominant wetland taxon is Restionaceae, while Cyperaceae values slightly increase and *Melaleuca* maintains consistently lower representation in this zone. Generally, there are relatively low charcoal particle abundances throughout the zone, although there are two small peaks at 144 cm (~9,300 cal yr BP) and 58 cm (~4,300 cal yr BP).

TOR F (5 to 0 cm; 400 to 0 cal yr BP*)*

There is a marked increase in eucalypt, myrtaceous shrubs, *Monotoca*, Asteraceae (Tubuliflorae) and *Melaleuca* representation and corresponding decline in Casuarinaceae abundances in this zone, which also observes the presence of *Pinus elliotti* for the first time in the record. Charcoal particle representation is virtually absent from this zone.

Welsby Lagoon (WEL) (Figure 4)

The uppermost 50 cm of the WEL core consists entirely of root matter from the sedge vegetation growing in the wetland and was not analysed in this study. The remainder of the sediment consists of highly organic peat becoming progressively more consolidated with depth. From 340 to 402 cm there is an increase in the sand content of the core and a band of sand is evident from 403 to 410 cm. The peat is dry and unconsolidated between 411 to 447 cm and the base of the record is marked by a band of sand from 448 to 458 cm. Eleven AMS ^{14}C dates provide an age-depth model for the record with a base age of 26,000 calendar years BP. The pollen record is dominated by sclerophyll arboreal taxa, particularly Casuarinaceae, although there is a greater abundance of rainforest, mainly *Araucaria* and palms, and sclerophyll herbs, predominantly Asteraceae (Tubuliflorae) from 450 to 405 cm (~26,000 to 20,000 cal yr BP). *Eucalyptus* and *Callitris* are the other key sclerophyll arboreal taxa, with the eucalypts having their highest abundance from 450 to 405 cm (26,000 to 20,000 cal yr BP) and *Callitris* peaking at 330 cm (~14,500 cal yr BP). Mangroves are absent from this record and pteridophytes comprise a relatively minor component of the total pollen sum. Aquatics have a similar importance in the record as in NCL and the key aquatic taxa are *Melaleuca*, Restionaceae and *Myriophyllum*, while sedges have much lower abundances than these taxa. The classification of the pollen undertaken on the core identified six zones.

WEL A (450 to 405 cm; ~26,000 to 20,000 cal yr BP)

This zone has the highest occurrence of *Eucalyptus*, myrtaceous shrubs, rainforest taxa and sclerophyll herbs, mainly Asteraceae (Tubuliflorae), *Tubulifloridites pleistocenicus* and chenopods, and the lowest abundance of Casuarinaceae (below 50%). *Melaleuca* and Restionaceae have their highest values in the record and the last occurrence of *Dacrydium guillauminii* is observed at 390 cm (~18,900 cal yr BP), while charcoal representation in this zone is very low, apart from a small peak at 410 cm (~20,200 cal yr BP).

WEL B (405 to 305 cm; ~20,000 to 12,500 cal yr BP*)*

There is a marked increase in Casuarinaceae values, with a corresponding decline in eucalypts and rainforest taxa in this zone. *Callitris* and *Monotoca* maintain similar values to the previous zone, while the sclerophyll herbs slightly decline and this is associated with a change in the dominant taxa from Asteraceae (Tubuliflorae) to Poaceae and the last occurrence of *Tubulifloridites pleistocenicus* [300 cm (~12,250 cal yr BP)] in the record. *Melaleuca* values decline from 360 cm (~16,700 cal yr BP) and maintain relatively low abundances for the remainder of the record. Restionaceae and *Myriophyllum* maintain similar abundances to the previous zone, while there is a small peak in Cyperaceae values at 340 to

330 cm (~15,200 to 14,500 cal yr BP). Charcoal representation is relatively low in this zone, except for a moderate peak at 350 cm (~16,000 cal yr BP).

WEL C (305 to 185 cm; ~12,500 to 7,000 cal yr BP)

Casuarinaceae values increase to between 73 to 87% of the pollen sum in this zone and maintain similar values until the final zone (WEL F), while *Eucalyptus* representation slightly increases in this zone. *Callitris* abundances decline in this zone, while *Dodonaea* and *Banksia* values increase and maintain their representation for the remainder of the record. Sclerophyll herbs, mainly Poaceae and chenopods, decline markedly, while *Myriopyllum,* Restionaceae and fern representation increases. The highest charcoal values are observed in this zone, with a peak at 290 cm (~11,500 cal yr BP), before returning to a similar representation as the previous zones.

WEL D (185 to 125 cm; ~7,000 to 4,300 cal yr BP)

This zone is similar to the previous one, except that there is another decline in grasses, Restionaceae and *Myriophyllum* representation and a slight increase in rainforest abundances. There is also a small peak in *Callitris* and chenopods around 180 cm (~6,800 cal yr BP) and pteridophytes obtain their highest abundances in the record. Charcoal values maintain relatively low values but there is a small and sustained increase in charcoal representation from 160 cm (~6,100 cal yr BP) that is maintained into the next zone.

WEL E (125 to 53 cm; ~4,350 to 190 cal yr BP)

Casuarinaceae reach their highest values in this zone (more than 75% in all samples), although there is some variability associated with their representation and corresponding alterations in eucalypt abundances. Rainforest values decline in this zone and there is a peak in *Callitris* from 105 to 95 cm (~3,300 to 2,700 cal yr BP). Asteraceae (Tubuliflorae) values increase from 110 cm (~3,600 cal yr BP) and grass values also increase from 95 cm, maintaining higher representation for the remainder of the record. Restionaceae and *Myriophyllum* abundances increase in this zone, while there is a marked decline in fern values. Charcoal representation is consistent with the previous zone, although there are two small peaks, one at 110 cm (~3,600 cal yr BP) and the other at 85 cm (~2,100 cal yr BP).

WEL F (53 to 50 cm; ~190 to 0 cal yr BP)

In the final zone there is a decline in Casuarinaceae representation (from 75 to 64%), which is associated with a marked increase in eucalypt, Asteraceae (Tubuliflorae), *Monotoca* and *Dodonaea* abundances. The presence of pine pollen is observed in the record for the first time and aquatic representation is consistent with the previous zone, while there is a decline in fern values. Charcoal abundances also decline in this zone.

Principal Component Analysis and Late Quaternary Regional Chronology (Figure 5)

The results of the Principal Component Analysis (PCA) for three records provide an indication of environmental change over the last 40,000+ years (Figure 5). From the commencement of NCL and TOR records to around 32,000 cal yr BP, relatively gradual environmental change is indicated by small sample to sample variation in PCA axis 1 scores. The early glacial (30,000 to 22,000 cal yr BP) is characterised by increased variability, particularly in the longer records (NCL and TOR). There is reduced variability in the dryland vegetation during the last glacial maximum, particularly in the TOR and WEL records. The last glacial interglacial transition and early Holocene vegetation (18,000 to 10,000 cal yr BP) is characterised by variability, with the remainder of the Holocene relatively stable.

There are a number of pollen taxa in the three records (Figure 5) that can help to resolve some of the chronological uncertainties associated with the radiocarbon derived age models for the three sites (Table 1). Key taxa include Casuarinaceae, *Araucaria*, *Dacrydium, Tubulifloridites pleistocenicus* (spineless Asteraceae) and *Banksia*. Casuarinaceae is the dominant taxon in the three records and alterations in its abundances are a key factor in the definition of pollen zones. In particular, the highest values of Casuarinaceae occur in the three records for almost all the Holocene, while lower abundances of Casuarinaceae are observed in both the NCL and TOR records during late Marine Isotope Stage (MIS) 3 (+40,000 to 30,000 cal yr BP) and then are, for the most part, more abundant in both records from 30,000 to 20,000 cal yr BP. Changes in *Araucaria* abundances, along with the disappearance of *Dacrydium guillauminii* and *Tubulifloridites pleistocenicus* are also important chronostratigraphic markers. *Araucaria* maintains high values during late MIS 3, and from 30,000 to 20,000 cal yr BP in the NCL and TOR records, and substantially declines during the deglacial period (18,000 to 11,700 cal yr BP) and the Holocene in all three records. In fact, there is elevated *Araucaria* representation from 27,000 to 22,000 cal yr BP in the three records, which also correlates with the last appearance of *Dacrydium guillauminii*. In addition, the disappearance of *Tubulifloridites pleistocenicus* from the three records provides another important biostratigraphic marker, with its last appearance occurring between 13,000 to 11,000 cal yr BP. Furthermore, *Banksia* values help to define the deglacial and the late Holocene, with abundances of this taxon being higher in all three records from 16,000 to 13,000 cal yr BP, but particularly increasing during the last 4,000 years.

6. Discussion

6.1 Comparisons with OZ-INTIMATE Climate Event Stratigraphy (CES)

The three records from North Stradbroke Island can be compared with the OZ-INTIMATE Climate Event Stratigraphy (CES) (Reeves et al., this volume a) and the more specific review of climate trends for the Australian temperate region (Petherick et al. this volume), leading up to, through and following, the last glacial maximum. The OZ-INTIMATE CES identifies eight key periods, namely: pre-glacial (+35,000 to 30,000 cal yr BP); early glacial (30,000 to 22,000 cal yr BP); LGM (22,000 to 18,000 cal yr BP); early deglacial (18,000 to 15,000 cal yr BP); late deglacial (15,000 to 12,000 cal yr BP); early Holocene (12,000 to 8,000 cal yr BP); mid-Holocene (8,000 to 4,000 cal yr BP); and the late Holocene (4,000 to 0 cal yr BP). Results of the three NSI records are discussed in the context of this framework.

The Native Companion Lagoon and Tortoise Lagoon records extend into the pre-glacial period (+40,000 to 30,000 cal yr BP), with both records indicating warm and wet climates relative to the subsequent periods. The high dunes site (TOR) was surrounded by a Casuarinaceae/eucalypt forest and/or woodland with a heath understorey, with the wetland itself supporting a paperbark (*Melaleuca*) swamp. At the low dunes site (NCL) located proximal to the exposed Moreton Bay, the vegetation consisted of Casuarinaceae/eucalypt forest with a shrub understorey assemblage. Relatively high values of rainforest pollen (i.e. >10%), particularly *Araucaria* and palms, suggest that a rainforest community was situated in close proximity to this site. This period was also associated with greater burning as suggested by the higher charcoal values.

The NSI pollen records during the early glacial (30,000 to 22,000 cal yr BP) indicate generally drier climate, consistent with the rest of Australia (Turney et al., 2006; Williams et al., 2009; Petherick et al., 2011; Petherick et al. this volume; Reeves et al. this volume b) and the broader Southern Hemisphere (EPICA, 2006; Barrows et al., 2007). There is substantial variation in precipitation during this period, reflected by the fluctuations of PCA axis 1 scores from the three records (Figure 5). The TOR record is indicative of the driest conditions of the three sites, with high values of grass and low representation of *Eucalyptus* and heath (*Monotoca*) pollen suggesting that the site was surrounded by open sclerophyll woodland with a grass understorey. This is further reinforced by low charcoal values reflecting lower fuel loads and associated fire regimes, as well as the virtual elimination of the Melaleuca swamp indicating lower water tables and a very dry climate. Similar changes are also seen in the NCL record, with a shift towards a eucalypt forest with a more open understorey dominated by heath and grass taxa, reflecting the drier conditions of the early glacial.

The substantial early glacial values of rainforest *Araucaria* in both the TOR and NCL records are seemingly at odds with the evidence for drier conditions. However, the increased representation of *Araucaria* may be associated with the more open vegetation allowing more effective wind transportation of *Araucaria* pollen to NSI, as has been suggested for this taxon in the ODP 820 marine core from north-eastern Australia (Moss et al., 2005). Alternatively, the greater rainforest representation in the three records, particularly NCL, may reflect the presence of rainforest refugia located along the palaeo-channel of the Logan River that was thought to flow across the dry Moreton Plain (Bay) along the southern edge of NSI (Evans et al., 1992; Harbison and Cox, 2002; Petherick, 2012). The WEL record starts during this period (at ~26,000 cal yr BP) and has similar patterns in pollen representation to the two other records. In terms of charcoal representation, both the TOR and WEL records suggest low intensity fire regimes, while the NCL record indicates less burning until 22,000 to 20,000 cal yr BP when there is a peak in carbonised particles. Site specific factors may play a role in these different burning regimes, with the NCL record reflecting wetter conditions with a greater presence of forest taxa supporting higher fuel loads as aridity increases during the

LGM, while both the TOR and WEL sites support more open sclerophyll communities unable to maintain a significant fire regime with drier climates.

The LGM (22,000 to 18,000 cal yr BP; as defined by the OZ-INTIMATE CES) is not clearly separated from the early glacial or the deglacial periods in the CONISS classification of the three records. This lends some support to the concept of an extended LGM, i.e. encompassing the entire glacial period, with two distinct dry periods at 31,000 cal yr BP and 22,000 cal yr BP, occurring across NSI (Petherick et al., 2008a). High abundances of Asteraceae in both the TOR and WEL records during the LGM period provide evidence of cooler temperatures. Increased representation of Asteraceae pollen (both Asteraceae Tubuliflorae and *Tubulifloridites pleistocenicus*) is commonly used to indicate cold climates in Australia (Dodson, 1983; Colhoun and van de Geer, 1986; Williams et al., 2006; Kershaw et al., 2007a). The NCL record does not record an increase in Asteraceae pollen and is indicative of substantial spatial variation in vegetation on NSI. In addition, the three records experience a decline in rainforest taxa and an increase in Casuarinaceae pollen suggesting increased regional aridity during the LGM. Another noteworthy feature of all three records during the LGM is decreased variability (as evident in the PCA) in the pollen taxa, which may reflect a more stable climatic regime during this period.

The last glacial interglacial transition (LGIT), (defined here as 18,000 to 12,000 cal yr BP and incorporating the early and late deglacial of the OZ-INTIMATE CES) in Australia, is characterized by increasingly warmer and wetter climate with rising sea levels, with some evidence of cooler and drier conditions corresponding with the Antarctic Cold Reversal (ACR) from 15,000 to 13,000 cal yr BP, though little or no evidence of the Younger Dryas (Turney et al., 2006; Williams et al., 2009; Tibby, 2012). All three NSI records have lower rainforest representation during the LGIT, which could reflect increased climate variability during this period, with rainforest taxa unable to grow on the low nutrient sandy soils of NSI under increased climatic variability, while sclerophyll taxa (particularly Casuarinaceae and eucalypts) are able to flourish (Ng, 1987; Donders et al., 2006). Again, there are differences in pollen representation between the three sites during the early deglacial (18,000 to 15,000 cal yr BP), with the coastal records (NCL and WEL) experiencing increased representation of Casuarinaceae and declines in grass and Asteraceae (Tubulifloreae) values. In contrast, the TOR record has increased representation of eucalypts and *Melaleuca* and a decline in grass values and is associated with the largest peak in carbonised particles in the record. This may reflect an increase in fuel loads related to the warmer and wetter conditions of the LGIT. These differences between sites may represent different local responses to the warmer and wetter conditions of the LGIT, with these conditions facilitating the growth of eucalypt forest and *Melaleuca* swamp around the TOR high dunes sites, while encouraging a Casuarinaceae-rich community at both the lower elevation NCL and TOR sites.

All three records provide evidence of increased climatic variability (compared to the LGM) during the LGIT, particularly the late deglacial and into the early Holocene, although this variability impacted each site differently. The NCL record has a peak in Poaceae, Cyperaceae and Restionaceae and charcoal values at 13,700 cal yr BP, with another charcoal peak around 10,500 cal yr BP, which is suggestive of drier environments. The WEL record has increased representation of Casuarinaceae ~14,000 to 12,000 cal yr BP and a peak (highest values in the record) in carbonised particles at 11,500 cal yr BP. The TOR record has a number of alterations including a sharp decline in *Melaleuca* at between 14,000 to 12,000 cal yr BP, a peak in *Hydrocotyle* (a wetland herb) at 11,800 cal yr BP and a peak in *Monotoca* abundances at 11,000 cal yr BP. These vegetation alterations at Tortoise Lagoon may reflect drier condition, with waters levels dropping resulting in a change from paperbark swamp to a shallow swamp dominated by *Hydrocotyle* (*H. verticillata* can grow in water depths up to 10 cm and is found on NSI) and finally to a wet heath. Increased climatic variability during the transition from the LGIT to Holocene is also observed in other temperate eastern Australia sites (Colhoun et al., 1982; Black et al., 2006; Williams et al., 2006; Kershaw et al., 2007a) and tropical north-eastern Australia (Kershaw, 1981; Turney et al., 2004; Turney et al., 2006), and higher resolution analysis of the NSI sites during this period may shed more light on the forcing factors behind this variability, as well as the role site variability plays in modulating the expression of climatic influences.

There is a great deal of similarity between the three NSI records for most of the Holocene period (i.e. last 10,000 years), with all of the records reflecting the development and dominance of sclerophyll open forest/woodland communities dominated by Casuarinaceae. In addition, all three records have lower representation of rainforest taxa, which likely represents the development of Moreton Bay and rainforest communities moving to the mainland in the face of rising sea levels. Notably, this is in contrast to the situation observed on Fraser Island where there is an expansion of rainforest taxa (in particular the gymnosperms *Araucaria* and *Agathis*) from 2700 cal yr BP to present (Donders et al., 2006). The influence of sea-level rise on the island's vegetation is demonstrated by the prevalence of mangrove pollen in the NCL record after ~9,000 cal yr BP.

In terms of broader climate change during the Holocene, all three sites experience wetter conditions through the early to mid-Holocene period (10,000 to 4,000 cal yr BP), with generally lower charcoal abundances reflecting less burning, compared to the late Holocene. These wetter conditions are also observed in other coastal eastern Australian records for this time period (Williams et al., 2009; Black et al., 2006; Kershaw et al., 2007a; Colhoun et al., 1982). In the late Holocene, climates of the region became drier, with a significant increase in burning in the NCL record and a slight increase in burning in the WEL and TOR records. In addition, both of the coastal sites (NCL and WEL) observe lower abundances of myrtaceous shrubs, *Dodonaea* and ferns during the late Holocene, which also suggests drier environments, although similar changes are not observed at the high dunes location (TOR) suggesting the influence of site specific variation on the pollen record. These changes are also observed in other Australian records, which are thought to reflect the increased frequency and intensity of ENSO-driven climatic variation (Shulmeister and Lees, 1995; Gagan et al., 2004; Haberle and David, 2004; Donders et al., 2007; McGowan et al., 2012).

6.2 Environmental Trends

The three pollen and charcoal records provide a picture of late Quaternary environmental change for North Stradbroke Island and the subtropics of eastern Australia that extends beyond the LGM. For most of this period, the island was dominated by sclerophyll arboreal taxa, particularly Casuarinaceae, although there were several periods in which sclerophyll herbs and/or rainforest were important components of the regional vegetation. Though each record covers a different time period, deposition of organic wetland sediment persisted throughout the LGM which is in contrast to the records from Fraser Island (Longmore, 1997; Longmore and Heijnis, 1999; Donders et al., 2006) and indicates that there was sufficient moisture to sustain the three wetlands. Moreover, this positive moisture balance was sufficient to maintain a dominance of trees through the glacial period, including the LGM. Such patterns are in contrast to other Australian long pollen records including those from the Wet Tropics (Haberle, 2005; Kershaw et al., 2007b) where herbaceous taxa dominate during glacial period (see Turney et al., 2006 and Williams et al., 2009 for reviews).

The environmental trends indicated in the NSI pollen records can also be linked with changes in synoptic-scale conditions. Previous studies have demonstrated large changes in synoptic-scale atmospheric circulation patterns occurring between glacial and interglacial stages (e.g. Bowler 1976). Proxy evidence indicates that the mid-latitude westerlies shifted equatorward during the LGM (Hesse 1994; Hesse and McTainsh 1999; Barrows and Juggins 2005; Cohen et al., 2011), allowing cold fronts to propagate further north (cf. modern) across the Australian continent (Kershaw et al., 2007a). Therefore, the very cold and dry environment of southern Australia would have been exposed to the regular passage of vigorous cold fronts, conditions conducive to enhanced dust entrainment and transport, as indicated by the aeolian dust records from NCL and TOR, which show peaks in far-travelled sediment flux during the LGM (Petherick et al., 2008a).

The increased climatic variability indicated in the NSI pollen records during the mid to late Holocene is also observed in other eastern Australian records, and has been attributed to the increased frequency and intensity of ENSO-driven climatic variation (Shulmeister and Lees, 1995; Gagan et al., 2004; Donders et al., 2007; McGowan et al., 2012). Intensified ENSO would have an impact on the strength and variability of the trade winds (Dodson, 1998), which would affect the precipitation regimes of eastern Australia, including the subtropics (Donders et al., 2007).

The pollen records from NSI also display evidence of millennial scale variability in vegetation which appear to be coeval with the timing of Heinrich (H) events (Bond et al., 1993; Dansgaard et al., 1993; Broecker, 1994). There do seem to be peaks in Casuarinaceae that coincide with Heinrich events (H1-4) in the three records, and there are some other additional alterations in the NCL record that are also coeval with H events, particularly a small increase in fern abundances at ~38,000 cal. yr BP (H4), a small peak in *Myriophyllum* at ~31,000 to 28,000 cal. yr BP (H3) and an increase in *Melaleuca* and Restionaceae abundances at ~23,000 cal yr BP (H2). Muller et al. (2008) demonstrated a link, through geochemical evidence, between Heinrich events (H1-3) and wetter periods in the Lynch's Crater record, tropical north-eastern Australia, with the suggested mechanism being a southward propagation of the Intertropical Convergence Zone (ITCZ) forced by cold Heinrich events. At NSI this would also likely lead to an increase in precipitation and the associated evidence of Heinrich event forcing of climate (i.e. increase in wetter taxa). Higher resolution analysis of the NSI records could be used to examine the evidence of Heinrich events and their environmental significance further in subtropical eastern Australia. In addition, the links between significant vegetation alterations observed at TOR during the late LGIT and very early Holocene and climate forcing needs further investigation, particularly if the ACR, YD or other mechanism are associated with these alterations and whether they are a regional feature or related to site specific factors associated with the TOR site.

One of the most interesting aspects of the three NSI records is the degree of difference between them. As discussed previously, the TOR record is from a high-dune setting, while the NCL and WEL records are from coastal low-dune environments. These local differences are most clearly expressed in how the vegetation at the three sites has responded to climatic variability during the late Pleistocene. Indeed, even in the two records from near the coast, there are substantial differences in the vegetation responses, with NCL showing generally wetter conditions across the last 26,000 years than the northern WEL record. The most obvious difference between the three sites is in their charcoal records, with the largest peaks occurring at different times and in response to different forcing factors, both climatic and human, or reflecting the patchiness of fire in the NSI landscape. At TOR and WEL the largest charcoal peaks occur during the LGIT, which may be associated with increased climatic variability that occurred during this period, as discussed in the previous section. In contrast, the NCL record has a number of charcoal peaks over the last 47,000 years that may be associated with a range of environmental factors. Key peaks in burning have been linked with climatic variability outlined above, as well as increased aridity during the LGM, but the role of people, as a potential ignition source in the NCL record needs to be considered. In particular, charcoal peaks between 47,000 to 40,000 cal yr BP can be linked to increased burning observed in records from northern Australia that are attributed to the arrival of humans (Turney et al., 2001; Kershaw et al., 2007b; Moss and Kershaw, 2007; Rule et al., 2012). This raises the possibility that the high charcoal abundance in the early part of the North Stradbroke Island record may be similarly linked to human arrival. This requires further investigation and may be achieved through the analysis of a longer (>50 ka) sequence recently extracted from Fern Gully Lagoon on the island.

A sustained increase in burning is also observed in the NCL record over the last 5,000 years, which may be explained by intensified human occupation and a drier climate. Archaeological investigation of the nearby Wallen-Wallen Creek site reveal the longest record of continuous human occupation in the south-east Queensland region (to at least 20,000 years ago), as well as increased occupation intensity over the last 5,000 years (Neal and Stock, 1986). However, significantly lower burning is observed in the TOR and WEL records, which both lack a sustained increases in charcoal values during the late Holocene, suggesting that people may have a minor influence on burning patterns of the central high dunes (TOR) and northern (WEL) parts of the island during this time. For North Stradbroke Island, it is apparent that climate plays a key role in burning across the region, but humans, if present, can substantially influence local fire regimes.

One factor that has consistently modified the three records is European settlement on the island. At the top of all three records, there is a clear change from Casuarinaceae to eucalypt, heath and grass taxa, which reflect alterations in fire regimes associated with European land management that has profoundly impacted the community dynamics of the island. Mooney et al. (2011) observe similar patterns across the Australian continent and suggest that European settlement has greatly influenced fire regimes and vegetation patterns on a continental scale.

7. Conclusion and Further Research

Three records of vegetation and burning from North Stradbroke Island provide the first continuous records extending past the LGM period (to 47,000 cal yr BP) for the subtropics of eastern Australia. These records indicate a positive moisture balance for most of this time through the near-continuous presence of arboreal taxa. Key alterations in vegetation appear to reflect broad-scale climate variation observed across Australia and outlined in the Oz INTIMATE CES (Reeves et al., this volume a), as well as the broader Southern Hemisphere (EPICA, 2006). However, there are some key differences, including the lack of a distinct LGM in the pollen record that add support to the presence of an extended LGM period for the subtropical region (Petherick et al., 2008a), no clear distinction between the early and late deglacial events, which we have defined as the LGIT, and extreme environmental variation, particularly in the TOR record, from the late deglacial into the very early Holocene (13,000 to 10,000 years). Furthermore, there are some substantial differences, particularly in charcoal representation, between the three records which suggest that site specific variation may play a key role in vegetation patterns and fire regimes, as well as the potential influence of microclimatic variation on pollen and charcoal representation in palaeo-records.

In terms of further research, higher resolution analysis of these records, particularly for the LGIT and early Holocene, would provide increased knowledge into sub-millennial variability across the OZ-INTIMATE CES time period, as well as potentially understanding the forcing factors behind this variability. Higher resolution analysis is crucial for identifying and determining the influence of abrupt climatic events such as the ACR, YD and Heinrich events in the subtropics. During the LGIT we see increased environmental variability in the NSI pollen records, but at the moment it is not possible to convincingly identify discrete climate reversals due to the resolution of the analyses and the insufficient age control.

Furthermore, as discussed previously, there are some issues associated with age control for the TOR and WEL records and an improved chronology, through further radiocarbon dates and refinement of the age model, would also substantially improve knowledge about the relationship between environmental change at these sites and the OZ-INTIMATE CES. Finally, there is scope to examine more records from across the Great Sandy Region of South East Queensland, which incorporates North Stradbroke, Moreton, Bribie and Fraser Islands, as well as the Cooloola sand mass on the mainland. There are numerous wetlands across the region that have the potential to significantly increase the spatial and temporal extent of palaeo-records for the late Quaternary period, as well as significantly improving understanding of environmental change in the sub-tropics of eastern Australia and links to broader climate change across Australia and the Southern Hemisphere.

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Table and Figure Captions

Table 1. Radiocarbon Dates for the three North Stradbroke Island sites. Data shown includes sample depth, laboratory, ^{14}C age and calibrated age (INTCAL 09; Reimer et al., 2009) for each of the cores. NC is the code for the samples taken from Native Companion Lagoon (17 ^{14}C samples); TOR is the code for the samples taken from Tortoise Lagoon (6 + pollen concentrate ^{14}C samples); and Welsby or WL is the code for samples taken from Welsby Lagoon (17 ^{14}C samples). Radiocarbon not used in the age models for each record have a NA in the calibrated age column.

Table 2. A list of pollen taxa, taxonomic affiliation and plant habitat for the three records. Also shown (in bold) and the taxa that have been included in the pollen sum for the three records.

Figure 1. Location of the pollen sites (NCL, TOR and WEL) from North Stradbroke Island, Queensland Australia and the Köppen climatic classifications for Australia (Köppen, 1931; Stern et al., 2000). Also shown are the major towns on the island (Point Lookout, Amity Point and Dunwich), current vegetation assemblages, as well as the important archaeological site, Wallen Wallen (Neal and Stock, 1986) and Brown Lake (significant perched lake) and Blue Lake (significant window lake).

Figure 2. The Native Companion Lagoon (NCL) summary pollen and charcoal record against depth (cm) and age (cal yr BP). Also shown is the lithology of the sediment core with black representing peat sediments and yellow reflecting sandy peats that occur towards the base of this record.

Figure 3. The Tortoise Lagoon (TOR) summary pollen and charcoal record against depth (cm) and age (cal yr BP). Also shown is the lithology of the sediment core with black representing peat sediments, brown reflecting lake muds and yellow representing sandy peats that occur towards the base of this record.

Figure 4. The Welsby Lagoon (WEL) summary pollen and charcoal record against depth (cm) and age (cal yr BP). Also shown is the lithology of the sediment core with black representing peat sediments and yellow reflecting sandy peats that occur towards the base of this record.

Figure 5. The Principal Component Analysis (PCA) and key pollen taxa plotted on a common age scale from the three sites. Also shown are the OZ-INTIMATE climate events (Reeves et al. this volume a, see text for details). LGIT=last glacial interglacial transition; LGM=last glacial maximum. The early and late deglacial of Reeves et al. (this volume a) have been combined into the LGIT.

Table 1. Radiocarbon Dates for the three North Stradbroke Island sites. Data shown includes sample depth, laboratory, ^{14}C age and calibrated age (INTCAL 09; Reimer et al., 2009) for each of the cores. NC is the code for the samples taken from Native Companion Lagoon (17 ^{14}C samples); TOR is the code for the samples taken from Tortoise Lagoon (6 + pollen concentrate ^{14}C samples); and Welsby or WEL is the code for samples taken from Welsby Lagoon (17 ^{14}C samples). Radiocarbon not used in the age models for each record have a NA in the calibrated age column.

Sample ID	Depth (cm)	Laboratory	Description	Age (^{14}C yr)	Age (cal yr BP)
NC-1-001	0.5	Waikato	Peat	540±36	640
NC-1-028	19.8	Waikato	Peat	1,745±37	2,016
NC-1-069	39.5	Waikato	Peat	6,353±50	7,341
NC-1-081	45.5	Waikato	Peat	6,176±47	7,136
NC-1-149	79.3	Waikato	Peat	9,222±65	10,656
NC-1-177	93.5	Waikato	Peat	10,130±73	11,705
NC-1-207	109	Waikato	Peat	11,478±79	13,623
NC-1-224	117	Waikato	Peat	12,714±90	14,691
NC-1-256	134	Waikato	Peat	13,467±98	15,561
NC-1-270	140	Waikato	Peat	13,570±100	15,680
NC-1-279	145	Waikato	Peat	13,586±100	15,699
NC-1-301	157	Waikato	Peat	14,762±116	17,058
NC-1-335	174	Waikato	Peat	15,999±132	18,487
NC-1-394	198	Waikato	Peat	19,311±157	22,314
NC-1-528	267	Waikato	Peat	28,684±456	33,144
NC-1-567	286	Waikato	Peat	33,187±816	41,317
NC-1-677	348	Waikato	Peat	35,757±1147	43,614

Tor-D-001	63	ANSTO	Peat	4,160±60	4, 654
Tor-D-002	122	ANSTO	Organic Muds	6,350±70	7,333
Tor-D-003	176	ANSTO	Peat	10,410±80	12,193
Tor-D-004	267	ANSTO	Peat	13,360±100	16,669
Tor-D-005	311	ANSTO	Peat	18,630±140	22,019
Tor-D-006	395	ANSTO	Peat	23,860±180	28,717
Tor-D-007	470	ANSTO	Sandy Peat	16,870±140	N/A
Tor-D-008	282	ANSTO	Pollen	16090±80	N/A
Tor-D-009	297	ANSTO	Pollen	14420±80	N/A
Tor-D-010	332	ANSTO	Pollen	15640±280	N/A
Tor-D-011	359	ANSTO	Pollen	15060±100	N/A
Tor-D-012	380	ANSTO	Pollen	16710±80	N/A
WEL 80 cm	80	Waikato	Charcoal	1,803±30	1,760
WEL 125 cm	125	Waikato	Charcoal	4,070±30	4,545
WEL 165 cm	165	Waikato	Charcoal	5556±26	6,347
WEL 251cm	251	Waikato	Charcoal	8043±30	8,940
WEL 287cm	287	Waikato	Charcoal	9903±38	11,310
WEL p304	304	Beta Analytic	Pollen	14250±50	17,010
WEL 342 cm	342	Waikato	Peat	18696±88	22,285
WEL p398	398	Beta Analytic	Pollen	16,350±70	19,490
WEL 414 cm	414	Waikato	Charcoal	29096±250	33,827
WEL 435 cm	435	Waikato	Peat	18320±90	21,800
WEL p438	438	Beta Analytic	Pollen	18,980±80	22,480

Table 2. A list of pollen taxa, taxonomic affiliation and plant habitat for the three records. Also shown (in bold) and the taxa that have been included in the pollen sum for the three records.

Pollen Taxa	Family	Plant Habit	NCL	TOR	WEL
Araucaria	Araucariaceae	Emergent rainforest tree	*	*	*
Podocarpus	Podocarpaceae	Canopy and subcanopy rainforest tree	*		
Dacrydium guillauminii	Podocarpaceae	Extinct rainforest shrub, closest extant affinity (based on pollen morphology) is on New Caledonia	*	*	*
Nothofagus moorei	Nothofagaceae	Canopy rainforest tree	*		*
Olea paniculata	Oleaceae	Canopy rainforest tree	*	*	*
Celtis	Ulmaceae	Secondary rainforest tree	*	*	
Trema	Ulmaceae	Secondary rainforest tree	*	*	
Sapotaceae	Sapotaceae	Canopy and second canopy rainforest tree	*	*	*
Sapindaceae (syncolpate)	Sapindaceae	Canopy and second canopy rainforest tree	*		
Cunoniaceae (tricolpate)	Cunoniaceae	Canopy rainforest tree	*	*	*
Elaeocarpus	Elaeocarpaceae	Canopy rainforest tree	*	*	*
Rapanea comp.	Myrsinaceae	Subcanopy rainforest trees and shrubs	*	*	*
Quintinia	Saxifragaceae	Mainly second canopy rainforest tree and one vine species	*		
Arecaceae	Arecaceae (Palmae)	Rainforest canopy and understorey trees and vines	*	*	*
Ficus	Moraceae	Rainforest canopy and understorey tree and vines	*		*
Syzygium comp.	Myrtaceae	Canopy rainforest trees	*	*	*
Flindersia	Rutaceae	Canopy rainforest trees	*	*	*
Lonchocarpus blackii	Fabaceae	Rainforest vine	*		
Malvaceae	Malvaceae	Rainforest or beach tree			*
Euphorbiaceae	Euphorbiaceae	Rainforest trees, shrubs and herbs	*		*
Macaranga/Mallotus	Euphorbiaceae	Secondary rainforest trees, often associated	*	*	*

		with disturbed sites			
Terminalia comp.	Combretaceae	Rainforest or beach tree	*		
Pipturus argenteus	Urticaceae	Rainforest or wet sclerophyll small tree or shrub	*	*	*
Pandanus tectorius	Pandanaceae	Beach tree	*	*	*
Myrtaceous shrubs	Myrtaceae	*Leptospermum*, *Baeckea* and *Tristania* shrubs that can occur on the beach, sclerophyll forest and heaths across NSI	*	*	*
Eucalyptus comp.	Myrtaceae	Sclerophyll canopy tree	*	*	*
Casuarinaceae	Casuarinaceae	Sclerophyll canopy tree	*	*	*
Callitris	Cupressaceae	Sclerophyll canopy tree	*	*	*
Ericaceae	Ericaceae	Heath shrubs and herbs	*	*	*
Monotoca	Ericaceae	Heath shrub	*	*	*
Dodonaea	Sapindaceae	Sclerophyll shrub	*	*	*
Banksia	Protaceae	Heath and sclerophyll secondary trees and shrubs	*	*	*
Protaceae shrubs	Protaceae	*Lomatia*, *Persoonia* and *Hakea* shrubs and secondary trees that can occur in sclerophyll forests/woodlands and heaths	*	*	*
Gyrostemonaceae	Gyrostemonaceae	Sclerophyll secondary tree	*	*	*
Acacia	Fabaceae	Sclerophyll canopy and secondary tree	*	*	*
Rhamnaceae	Rhamnaceae	Sclerophyll secondary tree and shrub	*		*
Pinus elliotti	Pinaceae	Introduced plantation tree		*	*
Poaceae	Poaceae	Dryland and Aquatic Herb	*	*	*
Asteraceae (Tubuliflorae)	Asteraceae	Dryland Herbs and Shrubs	*	*	*
Tubulifloridites pleistocenicus	Asteraceae	Spineless or short spined Asteraceae pollen grain, which has become extinct during the late Pleistocene. Thought to be a dryland herb	*	*	*
Hydrocotyle sp.	Araliaceae	Creeper and aquatic herb. Three extant species native to NSI. *H.*		*	

		acutiloba, H. penduncularis and *H. verticillata*			
Chenopodiaceae	Chenopodiaceae	Dryland herb and shrub, Also common coastal plant	*	*	*
Rutaceae	Rutaceae	Dryland herb	*	*	*
Brassicaceae	Brassicaceae	Dryland herb	*	*	*
Urtica	Urticaceae	Dryland herb	*		
Pimelea	Thymelaeaceae	Dryland herb	*		
Plantago	Plantaginaceae	Dryland herb	*	*	*
Acaena	Rosaceae	Dryland herb and shrub	*	*	*
Melaleuca	Myrtaceae	Wetland canopy tree	*	*	*
Cyperaceae	Cyperaceae	Aquatic herb	*	*	*
Restionaceae	Restionaceae	Aquatic herb	*	*	*
Myriophyllum	Haloragaceae	Aquatic herb	*	*	*
Triglochin	Juncaginaceae	Aquatic herb	*	*	*
Potamogeton	Potamogetonaceae	Aquatic herb	*	*	
Polygonum	Polygonaceae	Aquatic herb	*	*	*
Nymphoides	Menyanthaceae	Aquatic herb	*		*
Lemna	Araceae	Aquatic herb		*	
Drosera	Droseraceae	Carnivorous plant common in peat swamps	*		*
Cyathea type	Cyatheaceae	Rainforest tree fern	*	*	*
Lygodium	Lygodiaceae	Climbing fern	*		*
Lindsaea	Lindsaeaceae	Ground fern	*	*	*
Ophioglossum type	Ophioglossaceae	Ground fern	*		*
Gleichenia	Gleicheniaceae	Ground fern	*	*	*
Histiopteris	Dennstaedtiaceae	Ground fern and disturbance indicator	*		*
Monolete Fern Spores	Various	Ground fern	*	*	*
Lycopodium	Lycopodiaceae	Club moss	*	*	*
Selaginella	Selaginellaceae	Spike moss	*	*	
Avicennia marina	Acanthaceae	Mangrove	*		
Rhizophora stylosa	Rhizophoraceae	Mangrove	*		
Ceriops/Bruguiera	Rhizophoraceae	Mangrove (*Ceriops tagal* and *Bruguiera gymnorrhiza*)	*		

Figure
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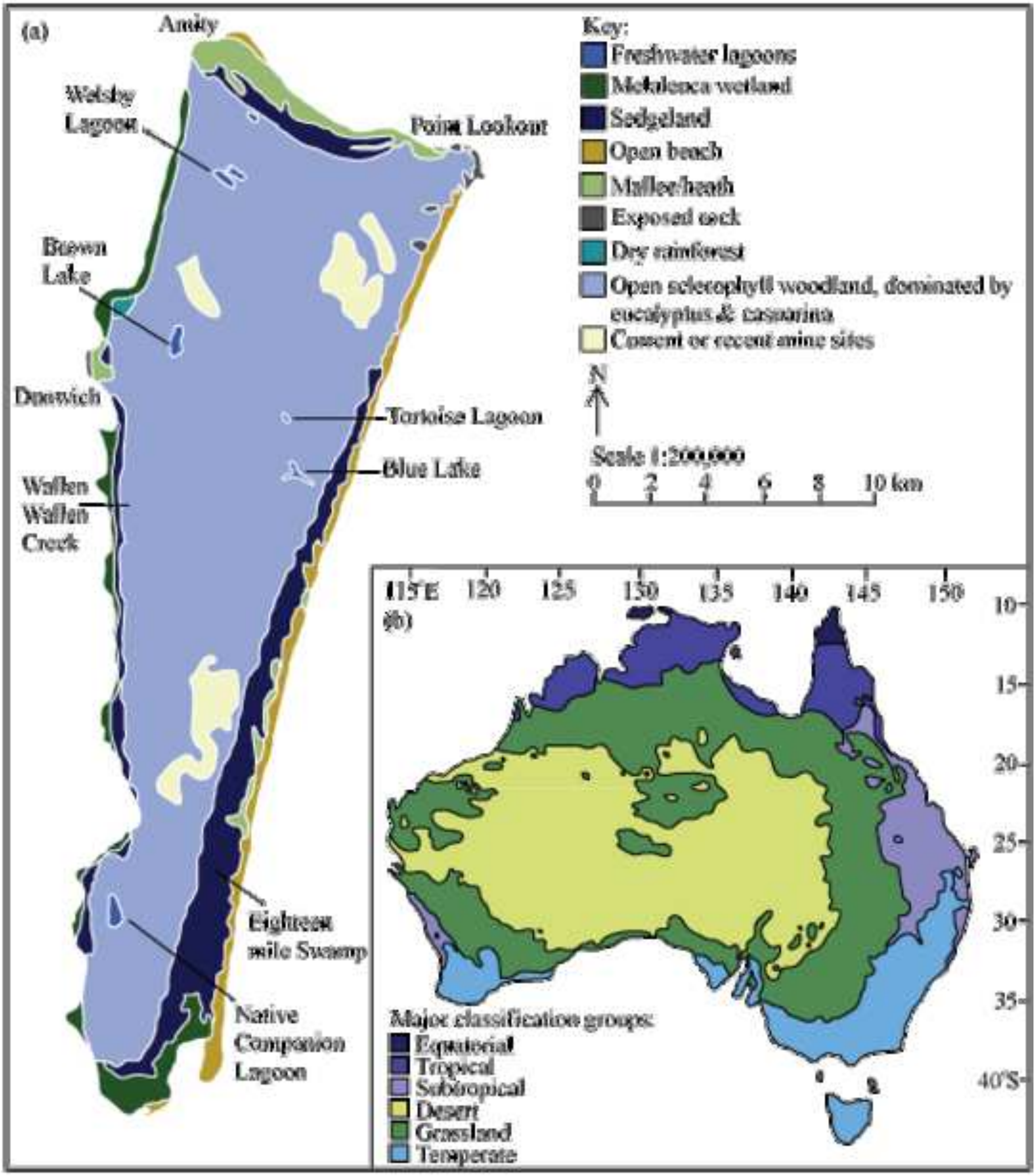

Figure 2
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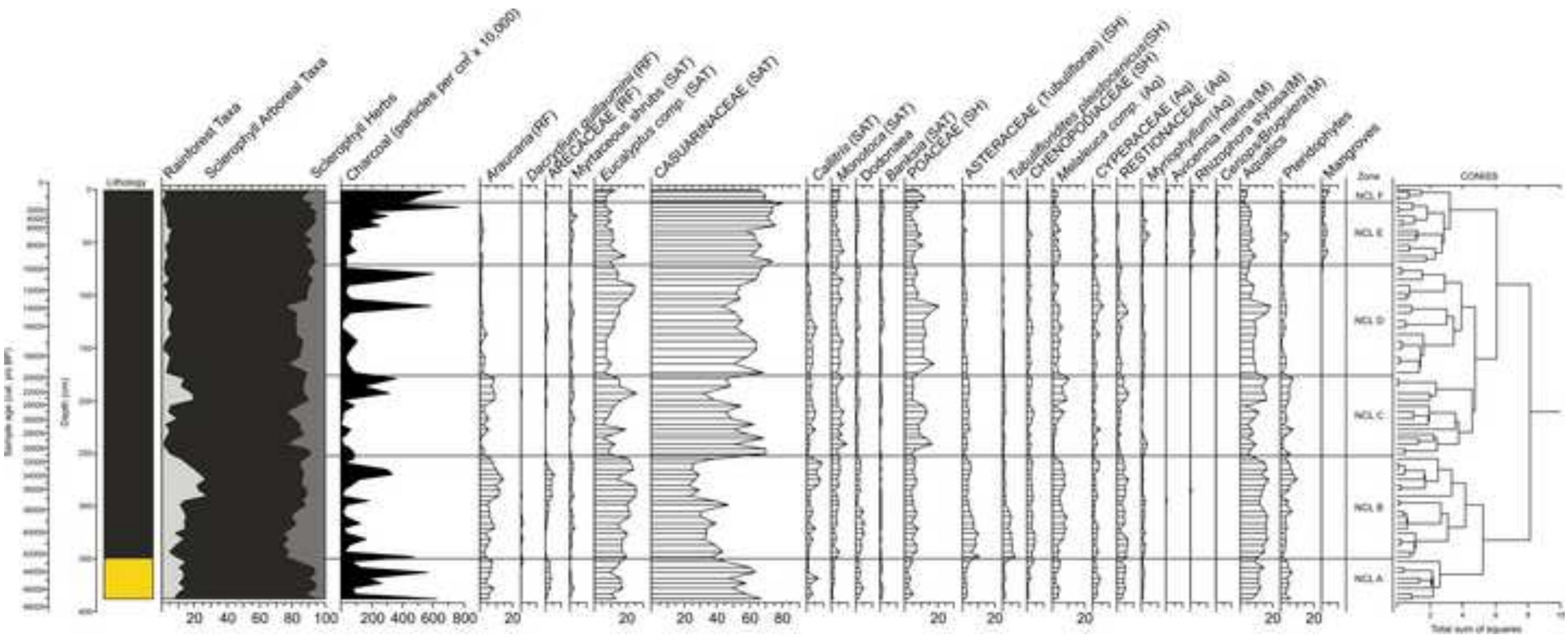

Figure 3

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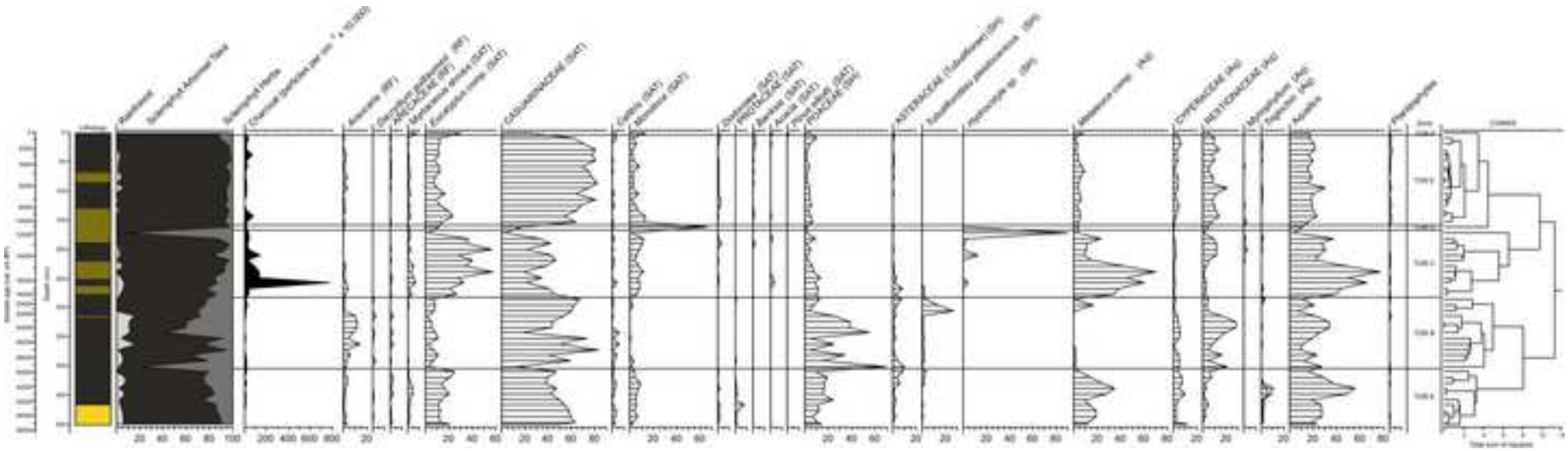

Figure 4
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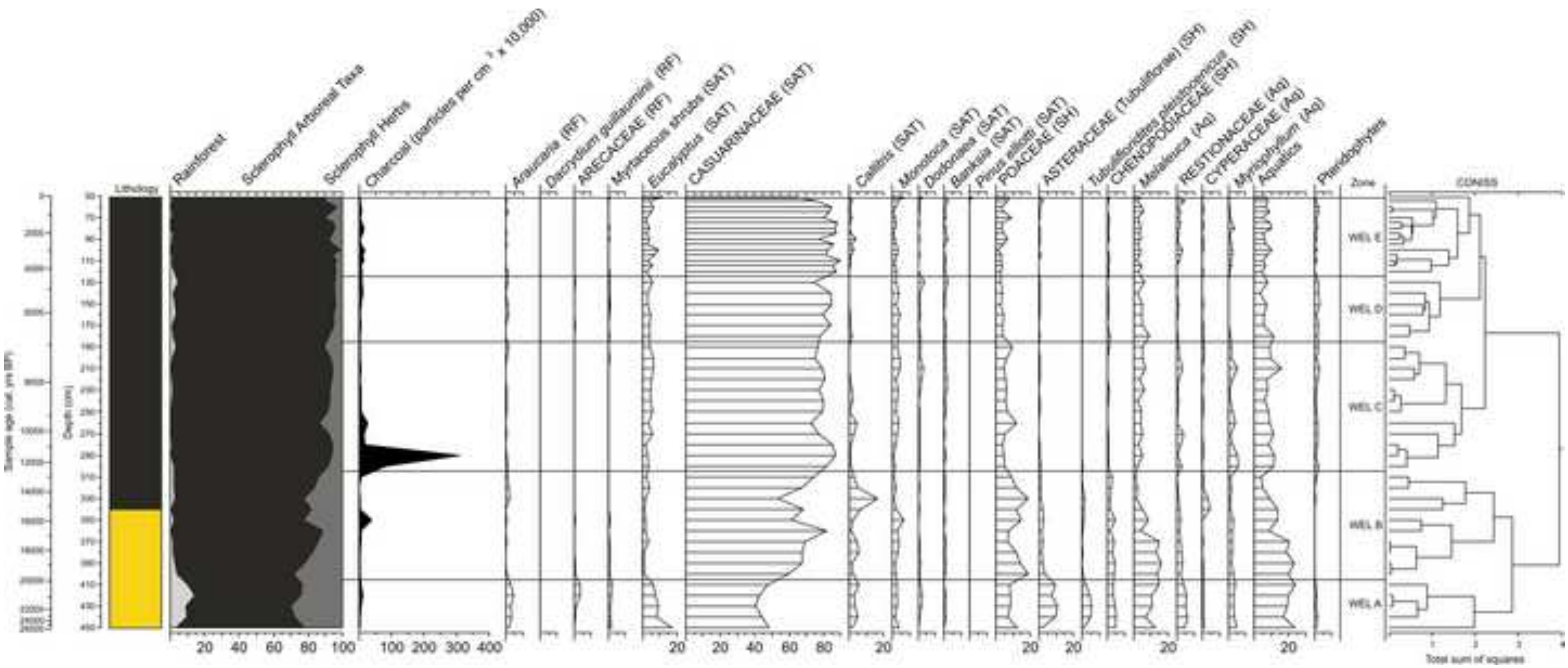

Figure 5

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