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Integrating charcoal morphology and stable carbon isotope analysis to identify non-grass elongate charcoal in tropical savannas

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Abstract Fire is inextricably linked to the vegetation that provides the fuel load. For palaeofire records to contribute meaningfully to the reconstruction of past landscape fire history, it is helpful to identify the vegetation that has been burnt, for example, grassy versus woody vegetation in tropical savannas. The morphological characteristics of charcoal particles can provide useful information on source vegetation type, and the aspect ratio of charcoal particles has been proposed to identify the contribution of grasses to environmental records. Stable carbon isotope analysis of pyrogenic carbon can also chemically identify the proportion of C_3 and C_4 biomass in charcoal samples but has yet to be widely applied alongside charcoal morphological analysis. Using carbon isotope analysis we demonstrate that C_3 sedges contribute elongate charcoal to a fire record where C_4 grasses are absent. These results challenge the widespread assumption that elongate charcoal is primarily or exclusively derived from grass, as most experimental studies demonstrating this relationship were conducted in environments where graminoids (grass-like forms) did not significantly contribute to available fuels. In turn, this complicates the simple interpretation of elongate aspect ratios for charcoal in fire records as direct proxies for the proportion of grasses in an environment, beyond differentiating temperate forests from grasslands. Minimal work to date has been done on separating charcoal derived from different graminoid types and future studies would benefit from the ability to differentiate graminoids including Poaceae and Cyperaceae in fire records. These results highlight the benefits of a multi-proxy approach to the interpretation of fire records in tropical savannas.

Keywords *Charcoal morphology · Pyrogenic carbon · Stable carbon isotopes · Palaeofire · Savannah · Northern Australia*

Introduction

The ability to determine the vegetation types contributing to charcoal in records of fires in the past (palaeofire) is essential for detailed interpretation of the complex relationships between fire, vegetation, humans and climate (Enache and Cumming 2006; Jensen et al. 2007; Scott 2010; Courtney Mustaphi and Pisaric 2014). The relative contribution of grasses provides key information in many environments, but particularly savannas, due to potential connections between grass biomass and fire (Cheney and Sullivan 2008; Ekblom and Gillson 2010; Prior et al. 2016; Leys et al. 2017; Cardoso et al. 2018; Wragg et al. 2018). Debate is ongoing regarding the relative influence of fire caused by humans, climate, and moisture availability, along with nutrient levels and ecological disturbances, on the dominance of grasses versus trees and woody vegetation across a range of temporal and spatial scales (Hoffmann et al. 2002; Murphy and Bowman 2007; Breman et al. 2012; Scott et al. 2012; Aleman et al. 2013; Colombaroli et al. 2014; Foreman 2016; Strickland et al. 2016; D'Onofrio et al. 2018; Feurdean and Vasiliev 2019).
While pollen is a powerful tool for reconstructing past vegetation, pollen preservation has anecdotally been observed as often poor in the arid and semi-arid environments that make up over one-third of the Earth's land surface (Wickens 1998) and 70% of the land surface of Australia (Department of Agriculture, Water and the Environment n.d.; Kottek et al. 2006; BOM 2016). In contrast, charcoal has high preservation potential (Figueiral and Mosbrugger 2000; Scott 2010). The determination of vegetation type from subfossil charcoal particles offers not only an insight into what vegetation was present, but also an opportunity to directly infer what was being burnt. Identification of fuels in fire records can improve our understanding of how vegetation structure or fire types, for example, tree crown versus ground surface fires, have changed through time (Feurdean et al. 2017). Characterisation of fire fuels can also reveal potential human influence such as the maintenance of open landscapes and suppression of woody vegetation through fire management (Rowe et al. 2019). It is therefore crucial that estimates of grass fuels are accurate, as over- or under-estimation of grass contributions could lead to the

reconstruction of past environments as more or less open with implications for the interpretation of interactions between fire, vegetation, climate and humans.

While charcoal has a long history as a palaeofire proxy (Iversen 1941), morphological analysis of charcoal particles to identify the fuel type has been developed much more recently (Umbanhowar and McGrath 1998). Experimental studies have demonstrated that grass, wood and leaves can produce charcoal with distinct length to width ratios (L:W) under laboratory conditions, with elongate(d) charcoal particles originating from grasses (Umbanhowar and McGrath 1998; Jensen et al. 2007; Crawford and Belcher 2014). Some studies have created classification systems based on charcoal morphological traits including overall shape, texture and presence or absence of internal structures in addition to whether a particle is elongate (Enache and Cumming 2006; Jensen et al. 2007; Courtney Mustaphi and Pisaric 2014); however, these systems are closely tied to the vegetation types of the ecosystems that were sampled to develop them, such as temperate forests. They therefore do not necessarily translate well to other biological regions such as tropical savannas (Rehn 2020, unpublished dissertation) or other depositional environments (Scott 2010). Additionally, Jensen et al. (2007) noted that the charcoal morphotype they called a “grass cuticle” can be produced by burning sedges (*Carex* etc.), and elongate charcoal found by Courtney Mustaphi and Pisaric (2018) may have been produced by burning conifer needles. Charcoal particle aspect ratios have been applied in a limited number of savanna field studies to identify grass versus non-grass contributions (Ekblom and Gillson 2010; Leys et al. 2015). Some studies such as Aleman et al. (2013) include modern ground cover data as a calibration for sediment sequences in which the last century is highly resolved, demonstrating a correlation between increasing elongate charcoal contributions and declining tree cover. Despite the relatively low uptake of charcoal morphological analysis within the palaeofire research community, many studies have identified the technique as valuable or promising (for example, Aleman et al. 2013; Hawthorne et al. 2018). These studies also recognise that the morphological approach requires further testing to refine the technique and to determine its efficacy in different environmental settings.

Stable carbon isotope analysis is a potential additional line of evidence to augment charcoal analysis for vegetation reconstruction. Analysis of $\delta^{13}C$ values in a sample can determine the relative contribution of plants using the C_3

photosynthetic pathway versus C_4 (O'Leary 1988). This is a useful method for determining grass contribution in environments where grasses are predominantly of the C_4 type, such as in the savannas of northern Australia (Hattersley 1983). As with charcoal morphological analysis, the application of stable carbon isotope analysis to chemically isolated pyrogenic (or black) carbon is also relatively recent (Bird and Ascough 2012; Wurster et al. 2012; Saiz et al. 2015). Studies by Saiz et al. (2015) and Bird et al. (2019) have demonstrated the utility of this technique in the tropical savannas of northern Australia, particularly for determining the relative contribution of tree versus grass biomass to the charcoal preserved in an environmental record; these studies also demonstrated that C_3:C_4 contributions are discernible even after accounting for potential fractionation effects as a result of burning (Saiz et al. 2015; Bird et al. 2019).

The present study seeks to critically assess the use of charcoal aspect ratios in the tropical savanna region of northern Australia to determine grass contributions, as well as demonstrate the interpretive power of a multiproxy approach to palaeofire research following the methods shown in Fig. 1. Sediment cores, surface samples and airfall charcoal traps were used for charcoal morphology and pyrogenic carbon isotopic analysis for this study to investigate how modern savanna vegetation is represented in a fire record. This study presents new charcoal and stable carbon isotope data from the savanna region of Cape York Peninsula, Queensland, northern Australia.

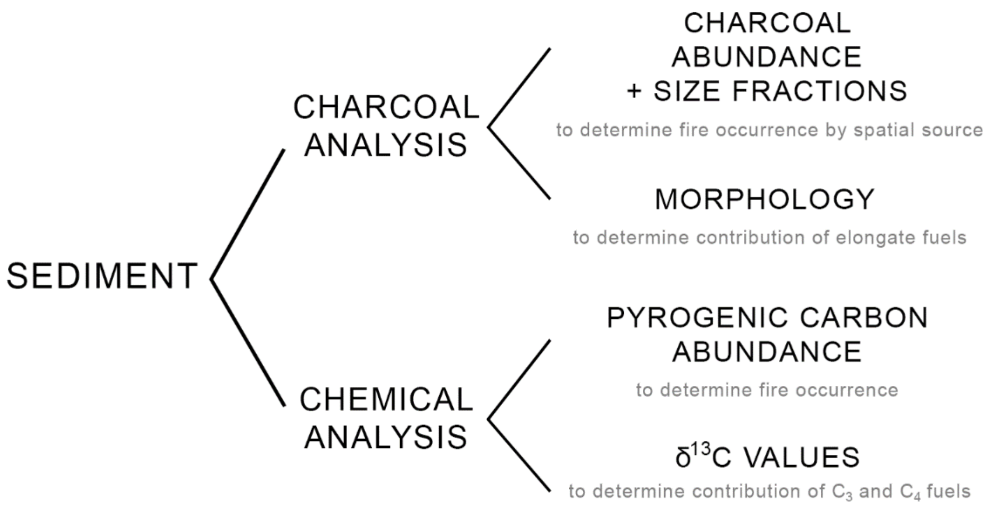

Fig. 1 Flowchart outlining the methods used in this study including the interpretive purpose for data derived from each method

Materials and methods

Site description of Sanamere lagoon

Sanamere lagoon (11.117°S, 142.35°E; 15 m a.s.l.) is located approximately 20 km south of Bamaga, close to the northern tip of Cape York Peninsula, far north Queensland, Australia (Fig. 2). The lagoon is approximately 1.5 km north to south and 2 km east to west. Sanamere lagoon is part of the Jardine River Wetlands Aggregation and is classified as a sub-coastal wet heath swamp (Department of Environment and Science 2018). The Anggamudi (also known as Angkamuthi), Wuthahti (alternatively Wuthathi) and Yadhaigana (alternatively Yadhaykenu) people are the traditional owners of the Jardine river catchment (Australian Institute of Aboriginal and Torres Strait Islander Studies 2014; Wilderness Society 2018), and Sanamere lagoon is part of the Apudthama Land Trust Area (Apudthama Land Trust 2018).

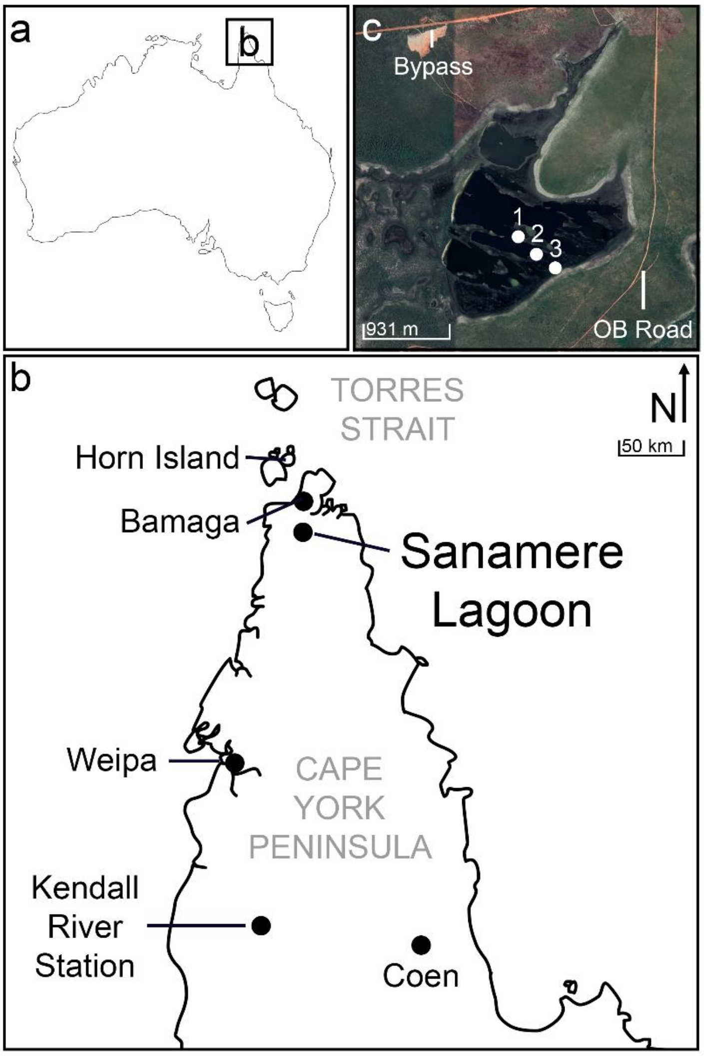

Fig. 2 Map of the study area; **a** location of the study area within Australia; **b**, key locations mentioned in the text; **c**, satellite image of Sanamere lagoon including the Northern Bypass road segment (Bypass), Old Bamaga Road (OB Road) and coring locations, 1 (centre; SAN1, SANFC, SANSURF1); 2 (midway; SANSURF6); 3 (edge; SANSURF10) (after Google Earth 2018)

Maximum water depth measured in April 2016 was 1.25 m. The majority of the lagoon is perennially wet, as determined by LANDSAT imagery for the period 1970-2018 (Department of the Prime Minister and Cabinet 2019). The lagoon has an approximate catchment area of 9 km^2 and lies in an enclosed basin surrounded by higher land, with the highest point (57 m a.s.l.) to the north-northeast of the lagoon, close to the current Bamaga Road (Geoscience Australia 2015; Department of the Prime Minister and Cabinet 2019). The Old Telegraph Track cuts across the eastern edge of Sanamere lagoon, created in 1887 to accompany the overland telegraph line that operated until 1987 (Horsfall and Morrison 2010). This track was initially the only access point for the northerly settlement of

Bamaga which was established in 1949-1952 (Queensland Government 2015), until construction of the Bamaga road. The construction of nearby roads has not contributed to erosion into Sanamere lagoon. The Old Telegraph Track forms the boundary of the Jardine River National Park to the east, gazetted in 1977 (Queensland National Parks and Wildlife Service 1996)

Climate and geology

The climate, according to the Bureau of Meteorology (BOM 2020a), has a mean annual rainfall ~1,760 mm measured from the nearest weather station at Horn island, approximately 55 km north of Sanamere. Rainfall is highly seasonal, primarily (~90%) occurring between December and April. Wind direction is also seasonally variable, predominantly from the north-northwest and southeast in January and July, respectively. Average daily temperatures range from a minimum of 23 °C (August) to a maximum of 32 °C (November-December). The highest temperature recorded between 1995 and 2020 was 37.9 °C (December 2002) and the lowest recorded temperature was 15.1 °C (September 2019). The highest recorded annual rainfall during 1995-2020 was 2683.8 mm in 2000.
The geology underlying Sanamere lagoon is Pleistocene sand with some silt and clay, bordered by deeply weathered Middle Jurassic to Early Cretaceous quartzose sandstone and micaceous carbonaceous siltstone known as the Helby Beds (Bureau of Mineral Resources, Geology and Geophysics 1977). Dominant soils in the area are deep bleached sands (Ca43: Uc2.21) and deep sandy mottled yellowish red earths (Mt9: Gn2.64) in Australian soil classification (Northcote et al. 1960-1968).

Vegetation and fire

Closed sedgeland with scattered *Pandanus* is found at the edge of Sanamere lagoon (Fig. 3), with emergent sedges extending in bands into the water, visible in satellite images, also observed by Brass (1953). Waterlilies and other aquatic plants are absent, with algae and sedges dominating in the water; sedges include dominant *Eleocharis* with *Schoenus* present. Also found on these wet sandy soils mainly close to the waterline are insectivorous *Nepenthes* (pitcher plants), adapted to source nutrients from captured insects due to the low nutrient content of the soil (Beasley 2009, pp 178, 228).

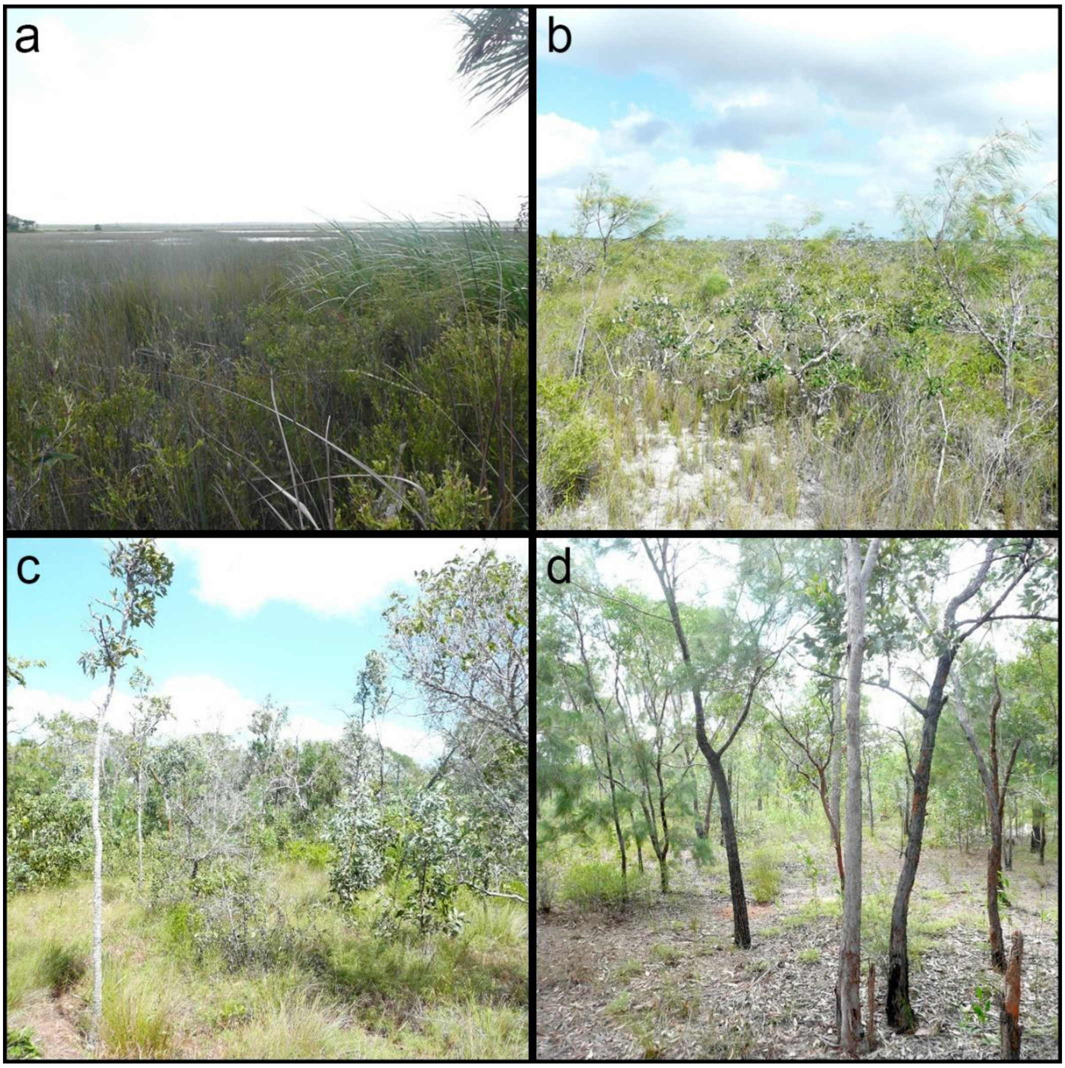

Fig. 3 Vegetation at Sanamere lagoon; a, shoreline vegetation comprised of Cyperaceae and scattered *Pandanus;* **b**. open heathland vegetation 50 m from the waterline; **c**, heathland to woodland transition at 300 m from the waterline; **d**, *Eucalyptus* woodland at 400 m from the waterline

This sedgeland community transitions sharply to open heathland which dominatesthe broader catchment of Sanamere lagoon (Fig. 3b); heathland is commonly found on nutrient poor sands (Beasley 2009, p 178; Neldner et al. 2017, p 191). The heath forms a shrubland, dominated by species of *Neofabricia, Asteromytus*, *Baeckea*, *Jacksonia*, *Hibbertia*, *Thryptomene, Allocasuarina* and *Grevillea* (Neldner and Clarkson 1995, p 72; Department of Environment and Science 2019). Trees are few, and when present, comprise *Grevillea pteridifolia* and *Banksia dentata*. Grasses are scarce and ground cover consists of clumped *Schoenus* sedges, mainly on wetter soil areas and drainage lines. Bare sandy soils are visible and leaf litter is minimal. Open heath vegetation extends approximately 300 m from the waterline before transitioning into *Eucalyptus* woodland.

Beyond 300 m from the waterline, the vegetation changes in structure (particularly height) and composition (Fig. 3c, d). *Eucalyptus* woodlands occur, dominated by *E. tetrodonta* with *Corymbia nesophila* codominant (Neldner and Clarkson 1995, p 116; Neldner et al. 2017, pp 108-109). Smaller sub-canopy trees are common and include *Acacia* species, *Grevillea glauca* and *G. pteridifolia* as well as *Livisonia* palm, with *Lomandra* and *Asteromyrtus* species present as shrubs. *Casuarina* occurs in patches, and in wetter, low-lying areas *Banksia* is present. Poaceae (grasses) dominate ground cover in this area and there is more leaf litter than found in the heathland. Termite mounds were recorded in the field in 2017 within the transition from heathland to woodland, and within the woodland. Indications of recent burning such as charcoal pieces and scorched woody debris were also recorded in the field in 2017 in the heathland to woodland transition zone. No herbivore grazing is known for the site, although some grazing by macropods such as wallabies is possible.

Burnt area data are available for a 20 year interval spanning 2000-2019, demonstrating that the area immediately surrounding Sanamere lagoon (both within the catchment and beyond) burned on average every 3 to 7 years (every year at its most frequent; 2002-2003, 2013-2014 and 2018-2019) according to Northern Australian Fire Information (NAFI 2020). However, burnt areas were recorded in 2000-2019 over the surface of the lagoon that are likely a result of error in the determination of burnt areas (P. Jacklyn, NAFI, pers. comm. 2019). Fire scars (burnt areas identified from satellite imagery) that extend substantially beyond the waterline may be assumed to represent real scars. Fires in 2000-2019 were primarily between August and December (NAFI 2020).

Site description: Coen and Kendall River Station

Coen and Kendall River Station are both located on Cape York Peninsula in open eucalypt woodlands with grassy understoreys (Fig. 2). Coen is a small regional town with a population of 364 (Australian Bureau of Statistics 2016) and Kendall River Station is an operational cattle station. Mean annual rainfall is ~1,073 mm measured from Coen airport, the nearest weather station to both sites. As at Sanamere lagoon, rainfall is primarily (~90%) recorded between December and

April (BOM 2020b). Winds are predominantly from the northeast and southeast in January and July, respectively (BOM 2020c). Average daily temperatures show a greater range than at Sanamere, from 16.9 °C (August) to 34.9 °C (December) (measured from Coen airport; BOM 2020b).

In the period 2000-2019, the area immediately surrounding Coen burned on average every 5+ years, with some isolated patches burning every year (2007-2009) and other areas going unburnt during this period (NAFI 2020). These fires occurred mainly between August and December and they can be classified as late dry season fires which are commonly associated with high fire intensities (Gill et al. 2000). Fires occurred within Kendall River Station on average every 1-2 years within the period 2000-2019, primarily between June and November with the earliest fires burning in May (2001, 2009, 2017-2019) (NAFI 2020).

Sample collection

Samples were collected from Sanamere lagoon during fieldwork in April 2016 and July 2017. Multiple sediment cores were collected by hand using a D section corer from a boat and using a raft-mounted hydraulic corer modified from Eijkelkamp equipment. The total sediment depth was 2 m, beneath a water column of ~1.25 m. Analyses presented here are from D section core SAN1 (1 m length, 5 cm diameter; 11.1231ºS, 142.3594ºE; collected April 2016) and core SANFC (11.1232ºS, 142.3599ºE; collected July 2017), a 15 cm diameter PVC short core (30 cm length) collected to capture the water to sediment interface for lead-210 analysis. Cores were contiguously sampled at 0.5 cm intervals, with samples combined for depths with insufficient sediment volume (D- SAN1). SAN1 0.5 cm increment sediment samples were halved, with one subsample processed for charcoal analysis and one for hydrogen pyrolysis analysis.

Surface sediment samples of the uppermost sediment to an approximate depth of 3 cm were collected by hand using sample bags. Ten surface samples were collected every ~50 m along a transect from the central coring position; three surface samples were analysed in this study representing conditions at the centre of the lagoon (SANSURF1), midway between the centre and the edge (SANSURF6) and just within the lagoon edge (SANSURF10) (Fig. 2; ESM Table S1).

Three air fall charcoal traps were constructed, consisting of a 30 cm diameter funnel and bucket above a PVC pipe, with an overflow valve containing two layers of mesh (125 µm and 63 µm) to prevent loss of accumulated particles. These traps were installed during fieldwork in 2016 at Sanamere lagoon (June 2016), Coen Ranger Station (13.941°S, 143.199°E; June 2016) and Kendall River Station (13.847°S, 142.069°E; April 2016) (Fig. 4). These locations cover various vegetation communities, dwarf heathland at Sanamere and open woodland at the other sites. Current land uses are Aboriginal Freehold land tenure, a regional township, and cattle farming, respectively. Charcoal traps remained on site for one year (2016-2017) to capture cross-seasonal fire and eliminate seasonal bias. Collected samples were sieved with 2 mm and 63 µm meshes, with the fraction between 2 mm and 63 µm retained for processing for charcoal analysis. Particles greater than 2 mm were discarded, as samples from the open woodland trap locations contained large uncharred organic remains such as twigs and leaves. Sample types, for example sediment cores and surface samples, and analyses of each type are outlined in Table 1 and described in detail below.

Fig. 4 Modern airborne charcoal trap on site at Kendall River Station; left, surrounding vegetation at installation in 2016; right, at time of collection in 2017, following a recent fire

Table 1: Overview of sample codes, sample types and analyses conducted on each sample type in this study.

Sample Code	Sample Type	Analyses
SAN1	D-section sediment core (Sanamere Lagoon)	Charcoal, hydrogen pyrolysis, stable carbon isotopes, radiocarbon dating
SANFC	Wide-diameter sediment core (Sanamere Lagoon)	Lead-210 dating, radiocarbon dating
SANSURF1, SANSURF6, SANSURF10	Surface sediment samples (Sanamere Lagoon)	Charcoal
SANFT, KENFT, COENFT	Airfall charcoal trap samples (adjacent to Sanamere Lagoon, Kendall River Station, Coen Ranger Station)	Charcoal

Radiometric dating

Lead-210 (SANFC) and carbon-14 (SANFC and SAN1) sample preparation and analysis of the Sanamere sediment core samples was done at the Australian Nuclear Science and Technology Organisation (ANSTO). These methods were selected to date the transition from older, pre-European conditions to the recent record which will reflect European management. Samples for lead-210 dating were taken from the uppermost 5 cm of the SANFC sediment core, 15 cm diameter, sliced at 0.5 cm increments. Samples were chemically processed to prepare polonium-210 and radium-226 sources for analysis by alpha spectrometry (Harrison et al. 2003; details in Rehn 2020, unpublished dissertation, and Rehn et al. 2021). Polonium-210 and radium-226 activities were then used to calculate total and supported lead-210, respectively.

Five bulk sediment samples and one hydrogen pyrolysis residue sample were prepared at 0.5 cm increments at regular intervals across the uppermost 50 cm of D section core SAN1 for AMS radiocarbon dating. One bulk sediment and one hydrogen pyrolysis residue sample were selected for dating from core SANFC. Bulk sediment and hydrogen pyrolysis residue samples for carbon-14 dating were pretreated using the ABA (acid, base, acid) method before combustion to CO_2 using the sealed tube technique followed by graphitisation; full details are in Hua et al. (2001). Carbon-14 AMS measurements were performed on the ANTARES 10 MV and STAR 2 MV accelerators at ANSTO Lucas Heights (Fink et al. 2004). Lead-210 dates were converted to calendar years BP (reported as years before 1950 CE). Lead-210 and radiocarbon dates were combined to form a Bayesian age-depth model using the rBacon package within *R* (Blaauw and Christen 2011; Blaauw et al. 2019; R Development Core Team 2013;). Radiocarbon dates were calibrated to cal BP as part of this process within rBacon using the southern hemisphere calibration curve SHCal13 (Hogg et al. 2013).

Charcoal

Charcoal was analysed from sediment core samples (sampled in 0.5 cm increments), surface sediment samples and airborne charcoal trap samples, following the procedure outlined by Stevenson and Haberle (2005). Samples were soaked in ~5% hydrogen peroxide for approximately 72 h to bleach organic matter, before being rinsed on nested sieves of 250 µm and 125 µm mesh. Samples in two macroscopic size fractions (>250 µm and 250-125 µm) were examined under a stereomicroscope at 20× magnification while suspended in water, with length and width measurements recorded using an eyepiece scale. Charcoal particles with an aspect ratio of 3.6 or greater were categorised as ‘elongate’, and less than 3.6 as non-elongate (Umbanhowar and McGrath 1998).

Hydrogen pyrolysis and stable carbon isotopes

Hydrogen pyrolysis and stable carbon isotope analysis was done on the SAN1 sediment core samples only, sampled in 0.5 cm increments. The modern fire trap samples could not be analysed due to insufficient material. Hydrogen pyrolysis was done to chemically isolate pyrogenic (black) carbon. Samples were freeze-dried and crushed using a mortar and pestle, and then loaded with Mo catalyst

(approximately 10% sample weight) with an aqueous/methanol solution of ammonium dioxydithiomolybdate [$(NH_4)_2MoO_2S_2$] and dried (Ascough et al. 2009; Wurster et al. 2012). Catalyst-loaded samples were inserted into a hydrogen pyrolysis reactor in the Advanced Analytical Centre at James Cook University, Cairns. Pressurised samples (15 MPa hydrogen with a sweep gas flow of 5 L min^{-1}) were heated at 300 °C min^{-1} to 250 °C before slower heating at 8 °C min^{-1} to a final hold temperature of 550 °C for 2 mins (Wurster et al. 2012).
Carbon content and stable carbon isotope composition ($\delta^{13}C$) before and after hydrogen pyrolysis were measured using a Costech elemental analyser fitted with a zero-blank auto-sampler coupled via a ConFloIV to a ThermoFinnigan DeltaV^{PLUS} using a continuous flow isotope ratio mass spectrometer (EA-IRMS). Stable carbon isotope results are reported relative to Vienna Peedee belemnite (VPDB) and precision (SD) with internal standards was better than ±0.1‰. The isotopic composition of pyrogenic carbon (PyC) was calculated in R using the equation given in Wurster et al. (2012). Stable carbon isotope values of -24‰ or less are attributed to C_3 plants while values of -15‰ or greater are indicative of a C_4 plants, with intermediate values representing a mixed source derived from both C_3 and C_4 biomass (O'Leary 1988; Saiz et al. 2018).

Results

Sediment cores

Lead-210 dating results identified the uppermost 5 cm of core SANFC as spanning the last ~160 years (Fig. 5); the monotonically decreasing unsupported lead-210 decay profile dictated the use of the constant initial concentration (CIC) model (Khrishnaswamy et al. 1971; Binford 1990), although ages were comparable when calculated using the constant rate of supply (CRS) model (Appleby and Oldfield 1978). An age discontinuity or unconformity was inferred between 5 cm (modelled lead-210 age of 90 cal BP ±12) and 10 cm (conventional radiocarbon age of 5,680±35) (ESM Tables S2, S3). A conventional radiocarbon age of 5,880±35 years BP for SAN1 (located 50 m away from SANFC) at 5 cm depth suggests that the uppermost 5 cm of core SAN1 is potentially approximately aligned with 5-10 cm in core SANFC. The top 5 cm of SAN1 is therefore taken to broadly represent late Holocene conditions at the site, comparable but not directly corresponding to the modern surface sediment samples.

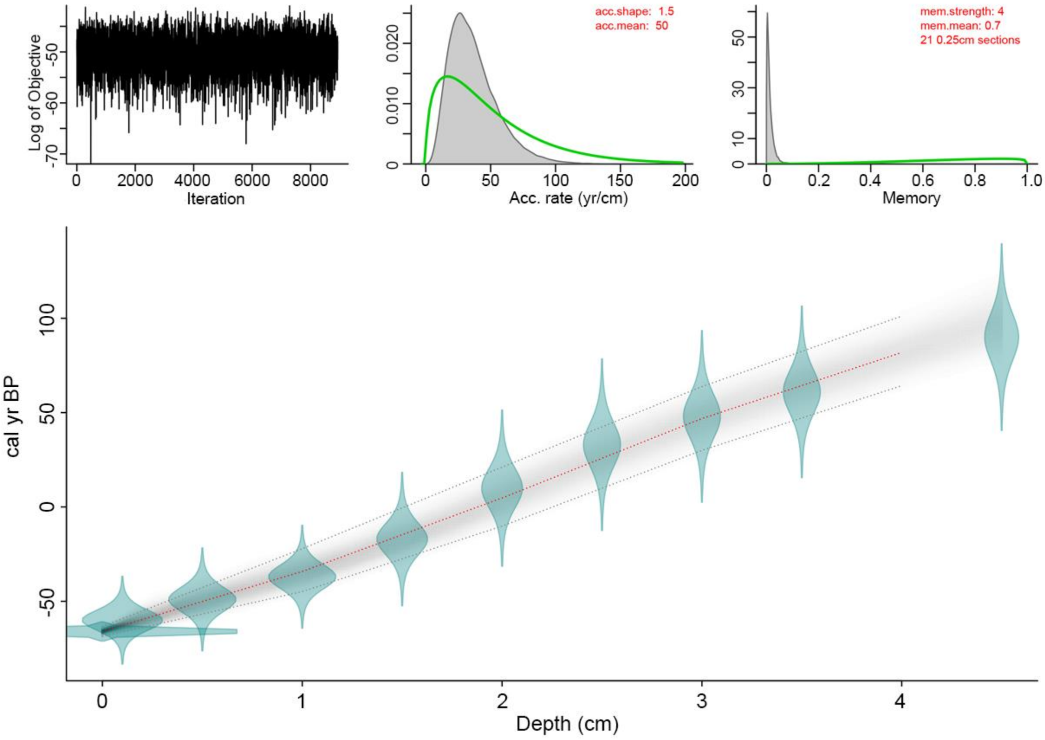

Fig. 5 Age-depth model for core SANFC generated using rBacon for R, displaying lead-210 dates only

The charcoal in the uppermost 5 cm of SAN1 shows elongate particle contributions of 17-71% (Fig. 6). Pyrogenic carbon (PyC) $\delta^{13}C$ values uniformly fall between -25 and -26‰.

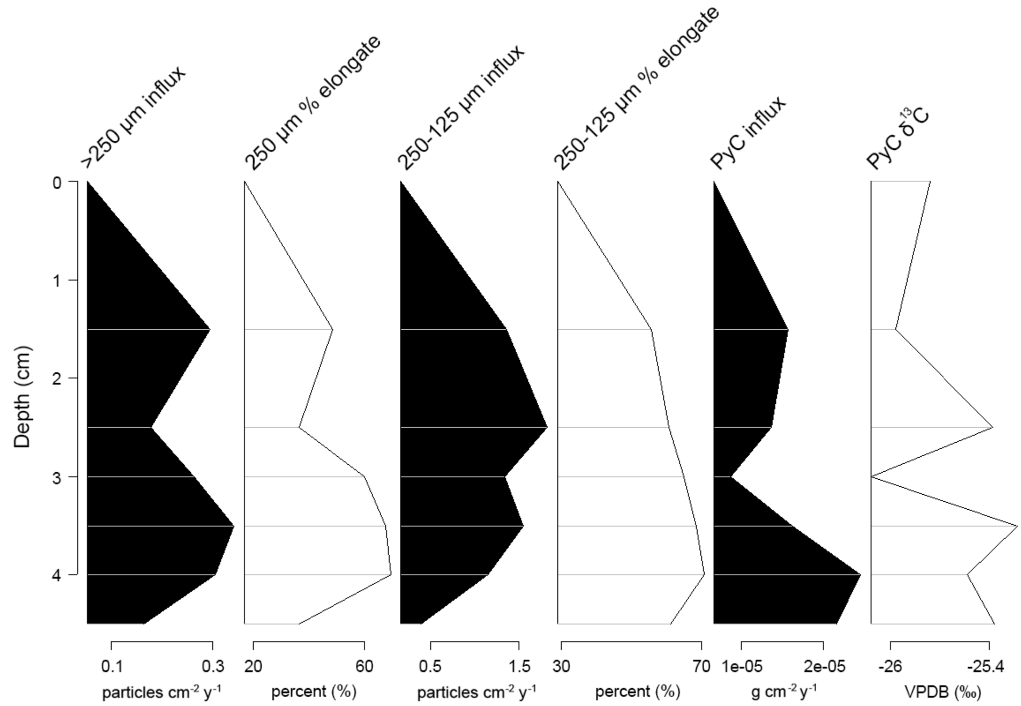

Fig. 6 Diagram showing charcoal influx, elongate charcoal particle percentages, pyrogenic carbon (PyC) influx and PyC $\delta^{13}C$ for the top 5 cm of SAN1

Surface sediment and modern airborne charcoal

Elongate charcoal particle percentages are high in all three analysed surface sediment samples, contributing approximately half of the charcoal particles present (Fig. 7a).

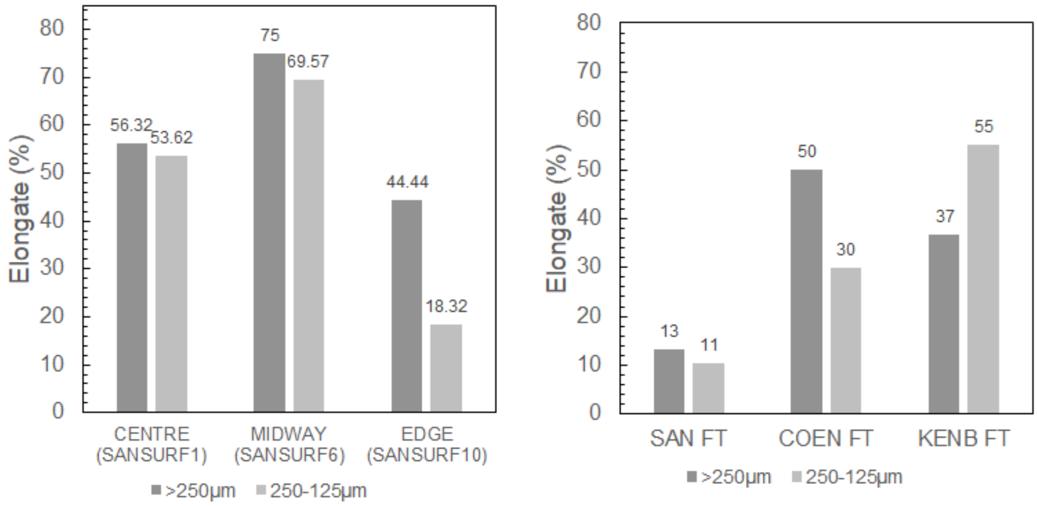

Fig. 7 Elongate charcoal particle percentages; **a**, surface sediment samples; **b**, modern airborne charcoal trap samples

Elongate charcoal particle contributions are high in the airborne charcoal traps located in open woodlands with grassy woodland understoreys at Coen and Kendall River Station (Fig. 7b). They were low in the Sanamere lagoon charcoal trap compared to surface sample charcoal from the lagoon. Elongate particles make up a higher percentage of the charcoal in the surface sample midway between the centre and edge (SANSURF6) than in charcoal trap samples from the open woodland sites (Coen and Kendall River Station).

Discussion

Fire is important in many ecosystems and its impacts are increasing in many parts of the world (Singleton et al. 2019; Mollinari 2020; Rogers et al. 2020) but relationships between fire and factors such as vegetation types and fuel distribution are complex. As such, accuracy in long-term records of fire is crucial, and this requires examination of methods used for studying fires in the past. This study contributes to the examination of palaeofire methods by critically assessing the use of charcoal morphologies to determine grass contribution. The results presented here demonstrate that the assumption that all elongate charcoal particles are derived from grasses is flawed, and that more robust vegetation reconstruction from fire reconstructions can be achieved by integrating morphological classification with stable carbon isotope analysis.

Elongate charcoal particles were abundant in all Sanamere lagoon charcoal samples, while stable carbon isotopes for SAN1 indicate that no significant C_4 grass-derived pyrogenic carbon is present. The uppermost sediments from SAN1 had between 17 and 71 % elongate charcoal particles while $\delta^{13}C$ values of bulk sediments as well as pyrogenic carbon were consistently ^{13}C-depleted, falling well within the range expected for C_3 plants (O'Leary 1988; Saiz et al. 2018). The presence of a grass component would result in substantially more positive $\delta^{13}C$ values; if the 17 to 71 % elongate charcoal particles were all C_4 material, $\delta^{13}C$ values would be expected to fall between approximately -17 and -22 ‰ (assuming minimum and maximum end members, respectively, of -15 and -24 ‰ for C_4 and C_3 biomass respectively; Saiz et al. 2018). That a C_4 component would be identified by the $\delta^{13}C$ value of pyrogenic carbon is demonstrated from open woodland savanna sites such as Marura sinkhole, from where the uppermost sediments representing conditions since ~1,900 CE yielded values of -21 to -22 ‰

for pyrogenic carbon, clearly identifying a mixed C_3:C_4 contribution to the charcoal at that location (Fig. 8; Rehn et al. 2021).

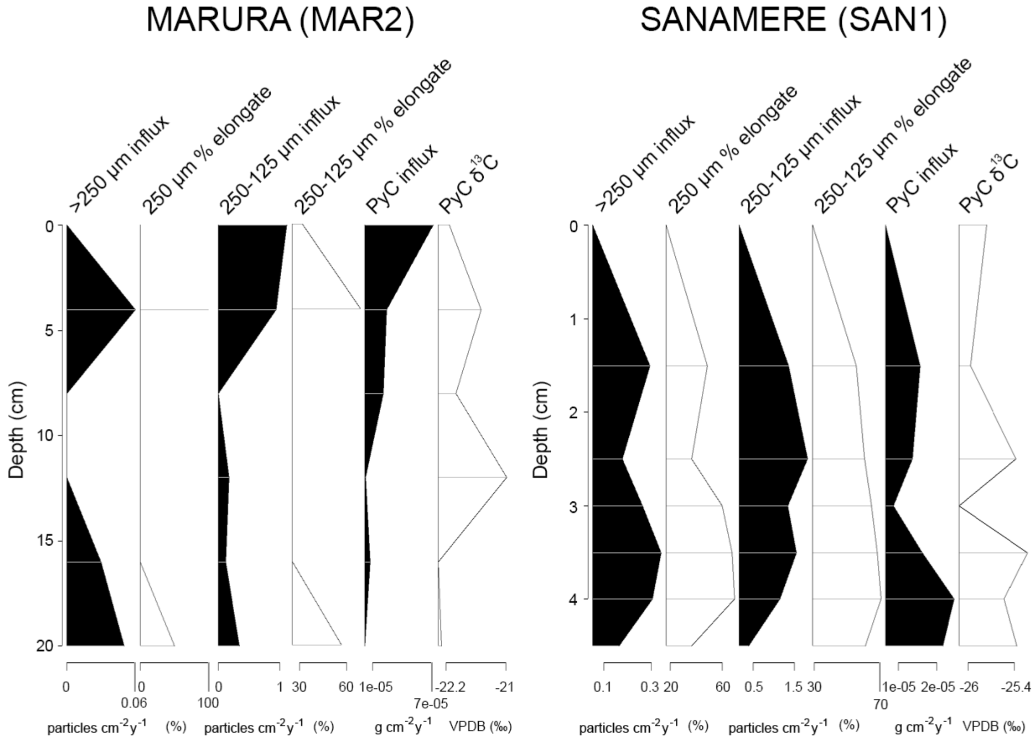

Fig. 8 left, charcoal influx, elongate charcoal particle percentages, pyrogenic carbon (PyC) influx and PyC δ^{13}C data for the uppermost 20 cm of Marura (Rehn et al. 2021); right, the uppermost 5 cm of Sanamere lagoon from Fig. 6

The absence of pyrogenic carbon derived from grasses in the sedimentary record suggests that the charcoal and pyrogenic carbon at Sanamere lagoon is locally sourced, as the observed grass biomass of clumps of Poaceae in the open woodland 300 m beyond the waterline is not represented in the record.

The δ^{13}C values of SAN1 clearly indicate a C_3 source for elongate charcoal at Sanamere lagoon. *Eleocharis* spike rushes, sedge family, present at the site have been identified as C_3 plants, with a δ^{13}C of approximately -26‰ or less (Bunn and Boon 1993; Boon and Bunn 1994). The elongate charcoal at Sanamere lagoon is therefore likely to be from burnt Cyperaceae. As the extensive bands of *Eleocharis* at the site are found on predominantly waterlogged sediments fringing the lagoon, the consistent presence of Cyperaceae charcoal suggests multiple, potentially recurring or seasonal, periods of local dryness, sufficient for the plants to burn.

The demonstration that burnt cyperaceous material contributed to this record demonstrates the interpretive power of combining stable carbon isotope analysis and charcoal morphological analysis. Charcoal aspect ratios alone would misidentify the elongate charcoal particles as grass-derived, while stable carbon isotopes would only identify that the vegetation burning was strictly C_3-derived; neither technique used in isolation could distinguish the presence of burnt C_3 Cyperaceae.

The modern airborne charcoal trap and surface sample data presented here demonstrate that not all savanna sites conform to the grass-derived assumptions of previous charcoal length and width studies (Umbanhowar and McGrath 1998). The Coen and Kendall River Station traps contained between 30 and 55 % elongate charcoal, representing the burning of the grassy understorey present at both sites. However, the Sanamere lagoon trap also contained elongate charcoal (11-13 %) and the Sanamere lagoon surface samples contained between 18 and 75 % elongate charcoal. The low elongate charcoal percentages in the Sanamere lagoon charcoal trap, compared to the sediment samples from the surface and SAN1, may reflect conditions during the collection period in 2016-2017 that were not dry enough for the sedgy vegetation to burn. This difference may also be caused by depositional factors, as the modern charcoal trap captured only airborne charcoal and not what was brought to the lake by overland water flow.

The misidentification or overestimation of grasses in palaeoenvironmental records can have significant interpretive consequences. Understanding tree/grass dynamics is important for many reasons including for land management, grazing, fire regimes and climate change responses, but landscape interpretations of palaeoenvironmental records may be in error if the grass contribution is not determined accurately (Bush 2002).

Conclusions

Fire is of significant ecological importance, especially in tropical wooded savanna landscapes, described as the ‘world’s most fire-prone biome’ (Andersen et al. 2012). Understanding the dynamics of fire and vegetation is particularly valuable for informing land management strategies and predicting ecosystem response to climate change (Ekblom and Gillson 2010; Breman et al. 2012; Veenendaal et al. 2018). Charcoal morphological analysis based on records of past environmental change preserved in lake sediments is a useful method for determining grass versus non-grass vegetation and is therefore capable of contributing to this understanding. However, the use of length-width ratios in ecosystems with both Poaceae and Cyperaceae is challenging and may overestimate grass contributions. A multiproxy approach using charcoal morphologies and stable carbon isotopes provides a more robust method for reconstructing past vegetation-fire dynamics.

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