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An examination of rockshelter palynology: Carpenter's Gap 1, north-western Australia.

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Abstract

Carpenter' Gap 1 is a large rockshelter located within the Kimberley region of northwestern Australia. The site provides valuable archives of late Quaternary palaeoecological information within an area known for a lack of deposits preserving long-term continuous botanical records. Previous studies of the macrobotanic, phytolith and wood-charcoal records from Carpenter's Gap 1 are in general agreement about changes in broad vegetation patterns over time but differ in the time scales used, in the representation of some species, and in the interpretation of changes - particularly on the degree to which the variations in the record represent cultural activities. An examination of palynology (the transport, deposition and preservation of pollen within the rockshelter environment) provides more detail to the vegetation patterns identified in these previous studies. In addition, because the pollen most likely reflects the vegetation of the site's surrounds over time rather than plants introduced into the shelter by people, interpretation can be more confidently linked to environmental change, and by inference climatic conditions. The pollen data reveals pre-glacial mixed wooded vegetation. From the beginning of the Holocene, tree loss occurred in a transition from monsoonal forest to thicket and eucalypt forest to woodland. Vegetation transition around the mid-Holocene suggests a shift in climate, becoming drier and more variable towards and into the late Holocene. The role of fire in the establishment of vegetation communities remains under investigation.

Keywords

Introduction

This paper presents palaeoecological results from an analysis of pollen and microcharcoal remains of sediments from Carpenter's Gap 1, a rockshelter located within the southern inland Kimberley, northwestern Australia (Figure 1). Carpenter's Gap 1 is an important Aboriginal cultural landmark, and provides an archaeological human-occupational sequence spanning over 45,000 years. The site has been used in determinations of human antiquity on the Australian continent (Fifield et al., 2001; Hiscock et al., 2016), in examination of the nature of human activity following colonisation (subsistence and demography) (Maloney et al. 2018; O'Connor and Veth, 2006; Vannieuwenhuyse et al., 2017), and in exploration of technology and artistic traditions (Donaldson and Kenneally, 2007; Langley et al., 2016; O'Connor and Fankhauser, 2001; Veth et al., 2018). Its unprecedented preservation conditions have also permitted macrobotanical (Dilkes-Hall et al., 2019; McConnell and O'Connor, 1997; McConnell, 1998), phytolith (Wallis, 2000, 2001) and wood-charcoal studies (Frawley and O'Connor, 2010) as sources of vegetation history, human plant exploitation and habitat modification. Through such themes Carpenter's Gap 1 has contributed not only to academic discussion, but also to technical/methodological advancements in archaeology and associated disciplines.

The purpose of the palynological analysis reported here is to provide (1) an additional line of biotic evidence describing Quaternary vegetation local to Carpenter's Gap 1, (2) to expand on environmental reconstructive detail for the southern Kimberley region more widely and, (3) to comment, where possible, on people-plant-landscape interactions through the course of site occupation.

Study Context: rockshelter palynology and interpretative considerations

Variations in pollen production, transport and preservation, and the deposition site itself, influence fossil assemblage development. Soil palynology (including archaeological sediment analyses) differs from palynology as traditionally performed on stratified waterlogged deposits (Hunt and Fiacconi, 2018). Deposition of pollen in lake/swamp sediments is a process of continuous accumulation. This process may be interrupted (on drying of the site), and deposits may become mixed (storm turbulence or faunal activity), but in essence all pollen at a given depth is of approximately the same age. In contrast, when pollen falls on an active soil surface, it is subject to both erosional and accumulation processes. Within a rockshelter, such sediment erosion and accumulation may be caused by both cultural and natural means (Pearsall, 2000; Dimbleby, 1985).

Rockshelters do not characteristically contain water-laid deposits (Hunt and Fiacconi, 2018). Moreover, being dependent on mechanical rather than chemical formation processes, rockshelters do not accumulate solution residues (Pearsall, 2000). Vannieuwenhuyse et al. (2016) and Wallis (2001) concluded for Carpenter's Gap 1 that water-related processes are not likely to have contributed to deposit formation, reporting no water infiltration through limestone and/or no prolonged periods of general wetness or seasonal wetting/drying. In evidence, an absence of carbonate-encrustation on site sediments (Wallis, 2001) and no water-born microstructures in thin-section (Vannieuwenhuyse et al., 2016) are consistent with continued deposit dryness. Conversely, rockshelters accumulate deposits derived from weathering of their bedrock, roof and walls and such physical breakdown was confirmed as a source of sedimentation in Carpenter's Gap 1 by Vannieuwenhuyse et al. (2016). Pollen, therefore, can be reworked from older sediments and/or rocks and incorporated into secondary sedimentary depositional contexts (Dimbleby, 1985; Wallis, 2000). Similarly, cultural sediment accumulations derive from the initiation or acceleration of rock wall disintegration as a result of human-induced micro-climate changes (e.g. fire-induced) and mechanical erosion (e.g. touching) (Dimbleby, 1985). Cultural sediment accumulation is also a product of people's introduction of new raw materials onsite, or the initiation/acceleration of slope instability and colluvial slope inwash as a result of increased firing or clearing of the landscape (Haberle and David, 2004). Owing to the elevated position of Carpenter's Gap 1 (see below) sedimentary influx from the surrounding landscape is unlikely, but both Wallis (2001) and McConnell and O'Connor (1997) suggest the onsite introduction of sediment and plant material via human agency.

The accumulation of sediments in rockshelter sites is added to via dust and other airborne detritus. Airfall of pollen in caves and/or rockshelters is widely reported (see Hunt and Fiacconi, 2018 and references therein), consistent with Wallis (2000) and Vannieuwenhuyse et al.'s (2016) record of site aeolian processes and contributions at Carpenter's Gap 1. Total pollen accumulation figures from airfall (when measured) tend to be low in rockshelters; lower than accumulation rates outside the shelter itself (Hunt and Fiacconi, 2018). A further contextual issue therefore is the volume difference between windborne pollen deposition within enclosed zones, and that in open-site environmental areas (Wallis, 2000; Pearsall, 2000). The placement of air-particle traps external to, and within Carpenter's Gap 1 (including atop the excavation area), demonstrated smaller collected quantities of micro-particles (carbonized material, phytoliths and pollen) in the latter versus former traps (Wallis, 2000). Importantly, pollen taphonomy review studies such as Hunt and Fiacconi (2018) revealed the proportions of different pollen as percentages of total pollen are comparable between the internal entrance areas of rockshelters to that close outside, suggesting palaeoenvironmental inferences are possible and not constrained by over-representations of local vegetation in pollen samples (c.f.

Carrión et al., 1998). Camacho et al. (2000) further confirmed the study potential of pollen from rockshelters by indicating that even small-volume within-cave sediments can realistically reflect not only local but regional vegetation of the site, when effort is made to understand the physical setting of the site, sediments and surrounds. In understanding the site, palaeoenvironmental reconstruction based on predominantly windborne pollen evidence may be affected by the direction and size of the opening of the shelter (Weinstein-Evron, 1994; Camacho et al., 2000). Hope (1982) argued that discrete archaeological pollen deposits are much more reliably interpreted if there is a regional off-site pollen sequence which they can be compared. Hunt and Fiacconi (2018) also advocated for paired and comparative pollen studies.

Differential preservation of pollen in sediments can bias the spectrum, notably by over representing the most resistant grains (Hunt and Fiacconi, 2018.) Oxidising agents and bacterial activity can have the same effect (Davis, 1994), and human activities, such as burning, can lead to overall poor preservation (Hunt and Fiacconi, 2018). Differential pollen preservation in archaeological sites, including caves, was discussed by Hall (1990), and Bryant and Hall (1993), and demonstrated an exponential decrease in pollen concentration with depth, marked by an increase in the percentage of 'indeterminable' pollen. As is typical of deterioration series, the number of identified taxa is greatest in the well preserved (near-surface) sediment.

In summary, and as an interpretative guideline, common themes are that much pollen deposited in rockshelter sites may be localised rather than regional in origin, dependent on the orientation of the site, its geological composition and sediment chemistry. The models for lake/swamp palaeoecological work are applicable, but the 'catchment' for pollen includes a direct cultural component. Hunt and Fiacconi (2018) stated that cave biostratinomic processes are usually regarded as linear. In caution, archaeological palynology sedimentation processes may be episodic rather than continuous, and post-depositional movement of pollen should be considered (Pearsall, 2000). A number of studies in Davis (1994) address one or more of these issues through case studies.

Study Context: site description and previous botanical data

Carpenter's Gap 1

Carpenter's Gap 1 is located along the northern margin of the Napier Range within the Windjana Gorge National Park, approximately 3 km from the Lennard River (Figure 1). The rockshelter is north to north-east facing ~ 25.0 m above the surrounding plains. The entrance height is ~ 20.0 m, with a floor area in excess of 50.0 m^2 and incorporating large boulder rockfall toward the opening (Figure 2). This rockfall is considered to have helped contain sedimentary deposits, provided weather protection and

facilitated the organic preservation for which the site is widely noted (Wallis, 2000; Watchman *et al*., 2005).

The Napier Range is a Devonian reef limestone complex, with carbonaceous, siltstone and sandstone components (Playford et al. 2009). The Range is positioned within the Dampier and Fitzgerald Botanical District boundary (Wheeler, 1992). These Districts include the southeastern extension of the Kimberley Plateau (to the north and east), as well as low-lying sandplains and dunefields bounded by the Pilbara and Great Sandy Desert to the south. Westward, Quaternary marine deposits form the coastal plain and alluvial deposits line the District Rivers. The entire region experiences a tropical semi-arid monsoonal climate with strongly seasonal rainfall and uniformly high temperatures (BoM, 2019).

Regional vegetation is predominantly tropical savanna woodland incorporating varied tree and shrub cover. In the immediate vicinity of the Napier Range, including Carpenter's Gap 1, three primary vegetation types occur. Sheltered gullies (typically with access to water) support pockets of vine-thicket (interchangeably termed dry-rainforest or monsoonal-forest), containing species of *Barringtonia*, *Celtis*, *Diospyros*, *Ficus*, *Harrisonia*, *Melia*, *Stemodia* and *Terminalia*. The drier, rocky slopes of the Range are dominated by spinifex hummock grasses (*Triodia* species) and low trees or shrubs of *Adansonia*, *Cochlospermum*, *Dodonaea* and *Grevillea* species. The plains extending out from the base of the Range are dominated by annual and ephemeral grasses (including *Cymbopogon*, *Enneapogon* and *Sorghum* species for example), as well as low growing herbs and shrubs (including *Hibiscus*, *Indigofera* and *Gomprena* species) and a scattered tree component characterised by *Eucalyptus*, *Grevillea* and *Terminalia* (Beard et al., 2013; Wallis, 2000, 2001; Wheeler, 1992).

The Archaeology

A 5.0 m^2 area of deposit, comprised of multiple 1.0 x 1.0 m squares, was excavated in 1993 and 1994 using archaeological techniques described in O'Connor (1995) and Maloney et al. (2018). Excavation was in 2.0 cm excavation unit (XU) divisions within stratigraphic units (SU) to bedrock. Maloney et al. (2018) provided a detailed description of stratigraphy. For this palynological discussion, an excavation section drawing is provided in Appendix A for further context. Sediments from Carpenter's Gap 1 square A2 were selected for pollen analysis (see below). Square A2 was excavated to a maximum depth below surface of 155.0 cm. Cultural material occurs throughout the sequence, but is most abundant through XU11-XU1. Stone artefacts, faunal bone, bird eggshell, freshwater mussel shell, crustacea and charcoal were recovered (Maloney et al., 2018; Hiscock et al., 2016). A variety of rock-art, including engravings and paintings also occur within the rockshelter (O'Connor, pers. comm.). Changes in the stone artefacts and faunal remains have been used to describe distinct 'pulses' (phases)

of site occupation beginning c.51,000 cal BP (Maloney et al., 2018). These phases are summarized in Table 1.

Macrobotanic analysis

Based on the patterning of macrobotanic remains McConnell and O'Connor (1997) suggested four main phases of environmental change. Dilkes-Hall et al. (2019) updated this interpretation to six phases while also correcting some earlier taxonomic misidentifications.

The earliest macrobotanic records (from 51,000 years) include *Terminalia* and *Vitex*, reflecting the presence of monsoonal forest. The data show abundant *Plechtrachne* and Cyperaceae in the time phase spanning 45,000 to 27,000 yr BP. Previous forest taxa decline, while new taxa such as *Mallotus* and *Premna* occur in low proportions. This environment is described as relatively dry, but with sufficient surface waters to maintain forest types (riparian, monsoonal), sedge-wetlands and perennial hummock-grasslands (Dilkes-Hall et al., 2019; McConnell and O'Connor, 1997).

The period 29,000 to 21,000 yr BP is similarly characterized by *Plechtrachne* and Cyperaceae, but in association with *Triodia*, *Grewia* and *Vitex*. The environment supported perennial grassland vegetation through to 25,000 yr BP, but with monsoonal forest and/or thicket growth, indicative of ongoing moisture to a level supportive of woody broad-leaf species. Forest-thicket associates decrease after 25,000 yr BP. Corresponding to a Last Glacial Maximum (LGM) phase (22,000 to 17,000 yr BP) the presence of Chenopodiaceae, Amaranthaceae, Cyperaceae and Poaceae are recorded (Dilkes-Hall et al., 2019; McConnell and O'Connor, 1997). During this phase the region supported a dry grassland-shrubland mosaic (McConnell and O'Connor, 1997). Dikes-Hall et al. (2019) however argued monsoonal forest taxa remained at accessible distances for human exploitation during the LGM, including *Celtis*, *Terminalia*, *Adansonia* and *Grewia*, although the distance travelled by people to exploit them may have been greater.

The deglacial period (from 18,000 yr BP) incorporated a mix of savanna and forest-type species, all at low densities (Dilkes-Hall et al., 2019). A Holocene shift (< 10,000 yr BP) demonstrates *Terminalia*, *Vitex*, *Celtis, Flueggea* and abundant *Adansonia*. Perennial grasses and sedges are virtually absent. The most recent history of Carpenter's Gap 1 is therefore dominated by deciduous and/or vine-thicket trees and liane-like species, but with little available surface water, still suggestive of a dry (or drying) regime (Dilkes-Hall et al., 2019; McConnell and O'Connor, 1997).

Phytolith analysis

Phytolith assemblages (Wallis, 2000, 2001, 2002) indicate grassland communities around Carpenter's Gap 1 at around 45,000 yr BP were similar to those of today. Diverse grassland is apparent (high

Panicoid and Chloridoid sub-family presence), most likely supported by medium level rainfall and readily available surface water. Low *Triodia* is interpreted as a spatial restriction of all arid-tolerate *Spinifex*-type grasses. Toward 30,000 yr BP a decrease in species diversity coincides with an increase in *Triodia,* indicative of decreasing temperatures and water availability. *Aristida* (tolerant of drier, but not cooler conditions) phytolith recovery presence reinforces climatic deterioration through 30,000 yr BP. Little additional change to the grassland communities occurred at the height of the LGM, but by the late Holocene ecology returned to those seen at the base of the site; *Triodia* decline with a corresponding increase in species diversity and probable water availability.

Arecaceae (palm family) phytoliths are present in abundance from 40,000 to 30,000 yr BP, in minor quantities approaching the LGM, after which they disappear from the record. This palm record (Wallis, 2000, 2001) suggests previously (pre-LGM) wider and more southern distributions than currently occur, reflective of once greater water availability through the inland southwest Kimberley. Palms gradually retract north with increasing aridity. Ulmaceae, with two phytolith forms linked to the vine-thicket occupants *Celtis* and *Trema*, is similarly present in the lower XUs then absent during the LGM. Unlike the palms, Ulmaceae reappear throughout Holocene-aged deposits.

Wallis (2000, 2001) found phytolith evidence of Cyperaceae through all XUs, with increased quantities during the LGM. Cyperaceae was attributed as culturally, rather than naturally introduced to the Carpenter's Gap 1 microfossil record. Sedges were highlighted as an important economic resource and indicative of (semi)-permanent water present somewhere near the site at times when it was occupied by people, and not directly informative on the palaeoenvironment. Diatom and sponge spicule presence were linked to Cyperaceae collection and therefore also seen as cultural representatives within the assemblage (Wallis, 2000, 2001).

Wood-charcoal analysis

High volume, well-preserved wood charcoal is reported by Frawley and O'Connor (2010). Less wood-charcoal was recovered (and with relatively low species diversity) through the early 42,000 to 30,000 yr BP phase. Sample identifications include *Acacia*, *Cochlospermum*, Myrtaceae (*Eucalyptus*), *Grevillea*, *Hakea*, *Planchonia* and *Terminalia* species, all considered indicative of a semi-arid environment. This environment encompassed tree/shrub orientated vegetation; the presence of *Terminalia* used to suggest restricted green pockets. *Terminalia* then increased significantly between 30,000-20,000 yr BP, coinciding with Ulmaceae and Tiliaceae representatives, *Corymbia*, diverse *Eucalyptus*, *Grevillea*, *Grewia*, *Hakea*, *Pouteria* and *Acacia* species. Through to 20,000 yr BP interpretation trends are two-fold; arguing continued small vine-thickets, even as surrounding environments dry. The exclusivity of certain *Grevillea* and *Acacia* species in this phase was seen as particularly reflective of a widely drying

environment, whereas *Grewia*, *Pouteria* and Tiliaceae existed in association with water-courses, vine-thickets and gorges.

The wood-charcoal record indicates that at the height of the LGM dry phase, open woodland taxa surrounded Carpenter's Gap 1. A predominance of Myrtaceae (*Eucalyptus*) and Proteaceae (*Hakea* and *Grevillea*) illustrates relatively homogenous composition. From the terminal LGM and through the Holocene there was an exponential rise in wood-charcoal quantity, linked not only to improved preservation but increases in human site use. *Adansonia*, *Brachychiton*, *Calthrix*, *Cochlospermum*, *Corymbia*, *Dodonaea*, *Eucalyptus*, *Ficus*, *Grevillea*, *Gyrocarpus*, *Hakea*, *Melaleuca*, *Petalostigma*, *Planchonia* and *Terminalia* species date to within the last 10,000 years, reflecting a moist environmental shift supportive of a wide range of vegetation ecologies (Frawley and O'Connor, 2010).

To date: botanical fossil data summary

In summary, these results (Dilkes-Hall et al., 2019; McConnell and O'Connor, 1997; Wallis, 2000, 2001; Frawley and O'Connor, 2010) indicate prominent grassland in the vicinity of Carpenter's Gap 1 between >43,000 and 17,000 yr BP, and again in the Holocene. This surrounding grassland was not entirely devoid of trees, and alterations in community composition initially reflected greater water availability in the earliest phases of the site (from 51,000 yr BP), followed by decreases in precipitation and temperature declines leading into aridity associated with the LGM. This is supported by the presence of palms at depth which later disappear from the sequence. The persistent documentation of monsoonal forest and/or vine-thicket taxa and Cyperaceae indicates the maintenance of small moist 'refuge' areas and at least semi-permanent water near to Carpenter's Gap 1 up until and through LGM aridity. These forest-type and/or vine-thicket associates, as well as Cyperaceae, proved to be economically important for Aboriginal inhabitants of the site. The Holocene period saw evidence of increased broad-leaved species with higher water requirements for growth. In quantifying Holocene climates, however, rainfall levels concluded as not being as high as those experienced at the time beginning 51,000 yr BP.

At certain points in time the different plant evidence proved complementary (e.g. diverse grassland pre-LGM, ongoing maintenance of forest/thicket types), and at others entirely unique information has been revealed (e.g. presence then absence of palms). Interpretative discrepancies do arise, predominately from differences in opinion on decay-biased datasets (recognizing negative effect of decay on botanical remains), ecological affiliations (the differential allocation of taxa to habitat), cultural activity (plant taxa as direct evidence of vegetation change verses archaeological data-set inclusion) as well as scale (how finely divided the time-averaged archaeological units used for each analysis were). Nevertheless, collectively the macrobotanical, phytolith and wood-charcoal data

provide a rounded profile of palaeovegetation (with climatic inference) and environment-people relations at Carpenter's Gap 1, more comprehensive than any one proxy record considered in isolation. Each additional line of evidence is best viewed as a refinement of information, rather than a strict correction of data. Such a role now extends to this paper's new palynological record.

Pollen and Microcharcoal Examination: methods

Pollen sample preparation followed standard techniques as detailed in Bennett and Willis (2001) and Brown (2008). Chemical preparations were selected to progressively remove sulphur compounds, carbonates, humid-acids, silicates and cellulose. *Lycopodium* spike additions served relative concentration calculations of both pollen and microcharcoal (black angular fragments <125 μm).

Only principal SUs and XUs were sampled for pollen. Sub-category units were eliminated for various reasons; some were insect cast layers (e.g. SU2a), hearth features (e.g. XU5a) or associated with ash rich sediments (e.g. XU6b, XU6c). In the treatment of all other samples (up to 10 cm^3 of sediment), particular diligence was required in the removal of dark organic/inorganic fine fractions, the majority thought to be burnt debris and/or ash material. Such effort was necessary in the provision of a sufficently 'clean' enough residue permitting pollen grain identification minus concealment (see Bryant and Holloway, 2009 for discussion and laboratory experimentation on this issue). In consequence, the microcharcoal record may have been distorted away from reflecting each sample's maximum burnt/charcoal material volume. Wallis' (2000: 277) phytolith analyses found similar issues with fine dark matter.

Radiocarbon dates, contributing interpretative guidelines for this study, were taken from Maloney et al. (2018), and summarized in Table 2. The chronological division of the Carpenter's Gap 1 square A2 sequence as discussed by Maloney et al. (2018) is followed.

Floral field-specimens collected from the Kimberley region by author CR, text reference material (e.g. Boyd, 1992), preserved reference collections of Monash University's School of Geography and Environmental Science, and online photographic sources (APSA members, 2007), assisted pollen identification. The Tilia suite of programs was used in data presentation, specifically the spreadsheet application Tilia (1.7.4) and graphing counterpart TGView (2.0.2) (Grimm, 1991). Pollen counts are expressed as a percentage of total pollen, a sum value up to 240 grains.

Pollen and Microcharcoal Examination: results

The pollen and microcharcoal results are presented in Figures 3, 4 and 5. Ecological affiliations of plant taxa as identified through pollen remains recovered from Carpenter's Gap 1 (square A2) are presented in Appendix B.

The most conspicuous feature of the Carpenter's Gap 1 diagram is the sharp decrease in pollen preservation with depth. Good pollen preservation and statistically appropriate concentration is limited to the upper six XUs (Figure 3), corresponding to the Holocene sequence in accord with Table 2. Through the deeper remaining XUs pollen grains were found to be highly degraded, contorted and sporadic in their presence. A complete record of undifferentiated/damaged pollen is presented (Figure 4) and discussed separately. The basal XU (XU61, Figure 5) also warranted separate discussion from the data that are illustrated in Figure 3.

Microcharcoal particles were observed throughout the Carpenter's Gap 1 sequence (Figure 3), and did not appear to deteriorate with depth. Increased deposition, incorporating progressively greater peaks, begins approximately 27,000-26,000 cal BP, at XU30 and again from XU24. Microcharcoal was most prominent between XU14 and XU07, corresponding to greater burning through and post the LGM. By the Holocene, microcharcoal records descend to a near minimum before values rise in the early-mid-Holocene (XU3, 4530-4420 cal BP) comparable to those recorded prior to XU14 (c.22500-21,700 cal BP). Concentrations of microcharcoal then decline through to the present day.

Prominent microcharcoal correlates with Maloney et al.'s (2018) description of site XUs as ashy, and Dilkes-Hall et al.'s (2019) record of higher proportion carbonized macrobotanical remains.

Both studies link ash and charring to increased Carpenter's Gap 1 visitation and/or overall human occupation intensity. Vannieuwenhuyse et al. (2017; Figure 16) showed similar charcoal particle recovery, and provided additional detail by discussing the nature of rockshelter burnt bedding deposits and their anthropogenic origin (repeated occupation with hot-fire maintenance). Natural fires were considered less likely due to insufficient fuel load on shelter surfaces to generate the firing required to influence such ashy sedimentary characters. As reported by Hunt and Fiacconi (2018), greater human use of onsite fire contributes directly to poor pollen recovery. In the majority, microcharcoal at Carpenter's Gap 1 is thus interpreted as derived from in situ human fires. Capturing off-site burning as a small proportion of results is supported by Wallis' (2000) air-particle trap results, as above (see also Scherjon et al. (2015) for discussions on off-site fire use by hunter-gatherers and implications for the interpretation of past fire practices in the landscape).

Excavation units 6-1, c.11, 200 cal BP to present.

Twenty-eight pollen types, representing a wide range of plant taxa, were identified in the Carpenter's Gap 1 samples. The assemblage is dominated (up to 92%) by the herb (or herbaceous sub-shrub) *Trichodesma* and the Myrtaceae family. All other taxa were recorded under 20% and notably 10% of the pollen sum (Figure 3).

Higher plant diversity is documented across the late Pleistocene-early Holocene transition. Although herbaceous taxa were initially at their most diverse (despite demonstrating lowest proportional presence up until the mid-Holocene), it is the greater tree and/or woody shrub presence through the early-mid-Holocene which dictate this trend (through to c. 4530-4420 cal BP). The highest values for rainforest associated woody taxa were maintained in the lowest XU samples, comprising members of the Euphorbiaceae (*Bridelia*, *Croton*), Acanthaceae, Tiliaceae and Sapindaceae families, as well as *Terminalia* and *Vitex* species. The sclerophyll woodlands, though dominated by strong Myrtaceae percentages (most probably *Eucalyptus*), also incorporated their most varied secondary canopy component in this early-mid-Holocene phase, notably *Erythrina* and other Fabaceae, with *Atalya* and *Pandanus*. *Terminalia* percentages probably further contributed to the early-mid-Holocene woodlands, as a taxon associated with both moist-forested and open sclerophyll habitat. Equally, Myrtaceae pollen may have contributed to earliest recorded rainforest group through genera such as *Syzgium.*

Between the early-mid to mid-late Holocene a shift is apparent in both the woodland and rainforest pollen. Percentage representation declines in Figure 3, combined with changes in pollen composition. A decrease and/or disappearance above XU4 (<6000-5850 cal BP, of all Euphorbiaceae, Acanthaceae, Tiliaceae and Sapindaceae as well as *Terminalia* and *Vitex* pollen coincided with the appearance of rainforest lianes and spreading (sub)shrubs (*Ampelocissus*, *Premna* and *Ficus*). From the mid-Holocene the Myrtaceae percentages continuously declined and non-Myrtaceous and/or malacophyll semi-deciduous secondary tree taxa are largely lost from XU3 (after 4530-4420 cal BP), replaced by arid-adapted, more strictly sclerophyllous *Grevillea* and *Adansonia* pollen. The late Holocene (<2000 cal BP) also included a record of the mistletoe family Loranthaceae.

Herbaceous percentages were high in all Holocene samples. The herbaceous group increased toward the surface to form the majority of the Carpenter's Gap 1 record, a trend closely associated with the rise in *Trichodesma* (Boraginaceae). All other herbaceous taxa (Solanaceae, Laminaceae, Tiliaceae, Commelinaceae) showed the opposing trend and decreased in percentage value between the early-mid into to late-Holocene with the exception of Malavceae which prominently appeared in XU2 and XU3. The Malvaceae pollen is most likely *Hibiscus* or *Sida* (see Appendix B and references therein).

Undifferentiated pollen: excavation units 61-1, >48,829-43,888 cal BP to present.

The pattern of undifferentiated and/or damaged pollen (Figure 4) follows that seen in the primary pollen diagram (Figure 3); pollen numbers were highest in the nearer-surface well preserved sediments before significantly declining. The undifferentiated/damaged pollen is presented separately so as not to detract from the identified grains. Had Figure 3 been illustrated with the high

numbers observed in Figure 4 (especially across XU5-XU3) percentage values would have distorted to unrecognizably low values. Most grains classified as unidentifiable through the Carpenter's Gap 1 sequence are suspected as being *Trichodesma* (Boraginaceae) and a potential tricolporate Fabaceae type, but were not able to be confidently allocated as such.

Basal excavation unit 61, >48,829-43,888 cal BP

The basal XU61 (Figure 5) demonstrates preservation quality and pollen concentrations comparable to the upper Holocene sequence XU6-XU1 (Figure 3). Microcharcoal is also well preserved and values exceed those observed during the LGM and post-glacial (XU14-XU7). XU61 pollen demonstrates high herbaceous percentage values, dominated by *Trichodesma* (Boraginaceae) and with minor Violaceae and Acanthaceae presence (Figure 5; Violaceae is the one record unique to XU61). The associated vine-thicket taxa show slightly higher diversity and collective percentage over the sclerophyll woodland representatives. Significant burning was recorded.

While the presence of pollen at this depth might be interpreted as resulting from vertical displacement from higher in the sequence, several independent lines of evidence suggest that this is unlikely to be the case. The grass phytolith assemblage at CG1 is thought to record a "largely culturally unbiased record of vegetation change in the local site vicinity" (Wallis 2001:111). The grass phytoliths in the lowest levels of Carpenter's Gap 1 are comparable to the grass assemblage in the late Holocene XUs, and found in the study area today, suggesting a relatively high diversity of grass species, moist habitat and at least medium level rainfall, and comparatively low levels of phytoliths derived from arid-associated species such as spinifex (Wallis 2001: 111). This is in marked contrast to the overlying LGM deposit which records an overall decrease in diversity of grasses and increase in spinifex (Wallis 2001:111-2). If vertical movement was occurring to any degree at Carpenter's Gap 1, we would anticipate that the phytoliths in the lowest deposits would have low diversity and an abundance of arid-associated grasses like consistent with the levels they moved from. Further, an independent test was carried out on the Pleistocene lithic assemblage at Carpenter's Gap 1 to determine if there was any evidence of size-sorting of artefacts in the lower deposits. This is a well-established means of testing for post-depositional movement of materials within archaeological deposits, with a variety of processes acting to lower small specimens and/or raise larger ones. No evidence of size sorting was found (Hiscock et al., 2016).

Discussion

Across the Kimberley, complex relationships exist between vegetation units (their primary plant alliances and secondary sub-alliances) and the edaphic, climatic physical environment (Petheram et

al., 1986). Suitable resolution exists within the Carpenter's Gap 1 pollen record to identify particular vegetation units (as reasonably well-defined floristic entities) and in turn to infer climatic conditions likely to support such vegetation. The new pollen record from Carpenter's Gap 1 provides evidence of vegetation from >45,000 cal BP and ecological change through the Holocene. The earliest vegetation cover is reasonably dense with a number of life-forms and a higher proportion of vine-thicket associates than woodland-grassland flora. More recently, patterns of change stem from a decline in tree cover from the mid toward late Holocene, interpreted as a response to declines in precipitation and/or greater variability in environmental water availability. Owing to poor preservation with depth no palaeoenvironmental comment may be provided for the period between *c.* 10-40,000 years and therefore discussion concentrates on the Holocene.

Phase 1: the early to mid-Holocene (c. 11,200 – 4,200 cal BP)

Beginning in the early-Holocene 'thicket' vegetation was present in the vicinity of Carpenter's Gap 1, consisting of tree and shrub formations as opposed to vine-dominated habits. This is classified as low closed monsoonal forest. An understorey of low tree and shrub species occured (particularly in canopy gaps, including but not exclusively Acanthaceae, Tiliaceae, Sapindaceae, Euphorbiaceae, *Croton*, *Vitex* and *Bridelia*) with a taller emergent crown of *Terminalia* species and Myrtaceae. There was virtually no ground flora within this community. Evident higher projective, broad-leaf foliage cover and forest-like growth is suggestive of moist climatic conditions, possibly incorporating degrees of climate uniformity (higher precipitation, reduced seasonality) but most likely promoting limited water loss through evaporation.

The monsoonal-forest would favourably occupy soil pockets on the escarpments and/or cliff-faces surrounding Carpenter's Gap 1 and would predominantly blanket the rocky scree/talus extending out from the rockshelter downslope to the low-lying plains (c.f. McKenzie et al., 1991). In these situations, the monsoonal-forest growth takes advantage of the more consistent to above-average water collections and storage taking place through rock-funnel action. Modern Kimberley forest/thicket formations occur as relatively discrete vegetation and floristic units. Few of their species extend to any great distance beyond the immediate fringing ecotone (Beard, 1976; McKenzie et al., 1991; Petheram and Kok, 2003). It is emphasised here that the monsoonal-forest formation may have largely existed as a discrete entity in the early to mid-Holocene phase; that the climate conditions combined with rock-water action of the limestone range prompted internal structural and compositional forest-like development across the scree/talus and plain to the north of the shelter, rather than any extensive spatial expansion.

On two points this local-to-site tendency is extrapolated out. First, species with ecological affinities akin to those of monsoonal-forest/thicket occur as (modern-day) narrow riverine fringes (Beard, 1976; McKenzie et al., 1991). The fringing vegetation of creeks (and the like) would have similarly increased in floristic complexity and structural density during the early and to mid-Holocene and may have merged with rocky-pocket monsoonal-forest units such as those associated with Carpenter's Gap 1 (as above). Second, under the favourably moist climate conditions select 'rainforest' (or more generally non-Myrtaceous) species would also have had the ability to establish stronger affiliations with 'sclerophyll' vegetation units, as can be seen in the Figure 3 early record of woodland secondary tree taxa.

It follows that greater relative floristic richness is apparent in the early to mid-Holocene sclerophyll-type vegetation units. The canopy trees comprise Myrtaceae/*Eucalyptus*. Projective foliage cover of the Myrtaceae/*Eucalytpus* is at its highest in the early-Holocene, reflective of water availability. It is feasible that canopy tree height was also high at this time, collectively suggestive of a eucalypt forest formation. Notable amongst the non-Myrtaceous understorey was a suite of evergreen and obligatory deciduous species, including *Erythrina*, *Atalya*, *Cajanus* and Fabaceae. *Pandanus* was also present, confirming moist environmental conditions. Broad-leaf herbs and sub-shrubs (Commelinaceae for example) grow with grasses on the ground-storey. It transpires that through the Myrtaceae/*Eucalytpus* canopy ample penetration of light to the lower layers occurs, sufficient to support the described tree, shrub and ground compositions (c.f. Brock, 2001). The early to mid-Holocene sclerophyll forest is therefore classified as an open forest.

The open Myrtaceae/*Eucalytpus* forest occurs on the lowland plain stretching from the base of the Napier Range, and would extend up to where the rocky scree/talus thins out at the base of Carpenter's Gap 1. In this respect the open forest likely grades into the monsoonal-forest vegetation unit.

Phase 2: the mid- to Late-Holocene (≤ 4,200 cal BP)

In the mid-Holocene the low closed monsoonal-forest characteristics changed. The upper pollen record was marked by the absolute or near-to disappearance of Acanthaceae, Tiliaceae, *Croton*, and *Vitex. Premna, Ampelocissus* and *Ficus* presence was favoured. These changes represented a new competitive advantage of lianes and small trees (tending to sprawling shrubs) into the late-Holocene. Here, the closed forest formation was replaced by an irregular in height, broken-canopied vine-thicket and monsoonal-scrub vegetation unit. The earlier Holocene broad-leaved evergreen foliage cover was reduced, and the vegetation incorporated microphyll, deciduous tendencies in the later Holocene. These transitions are proposed to be driven by overall drier climatic conditions or increased rainfall periodicity. Plants would be required to either avoid seasonal water stress or regulate their water

usage. A drier climate does not preclude an ongoing taller emergent crown of *Terminalia* and Myrtaceae, but does suggest that their response behaviour would also be deciduous. *Adansonia* is recorded as occupying the modern-day lower rocky-slopes of the Napier Range (Wallis, 2001) and this genus may therefore also have formed part of the emergent crown from the mid-Holocene. *Adansonia* may also characterize an ecotone between the monsoonal vine-thicket-scrub and sclerophyll communities occupying the lower lying plain (as described below).

The mid- to late-Holocene vine-thicket and monsoonal-scrub may no longer have occupied smaller soil pockets positioned at elevation on the site surrounding cliff or escarpment faces. These locations would no longer have been locally humid settings but more arid. The plant community would however have remained as a discrete entity across the rocky scree/talus, albeit in a more scattered manner compared to the previous 'blanket'. The microrelief of the rocky scree/talus would have maintained its function in concentrating any available rainfall above that of the surrounding landscape, proving crucial in moisture preservation and generation of edaphic conditions capable of preventing free drainage. Undoubtedly a drier, periodic and/or variable climate would have left the vine-thicket and monsoonal-scrub vulnerable to fire. Therefore, while a concentrative availability and preventative loss of moisture is in itself important, it could be that the rocky slope's provided a refuge that ultimately permitted this vegetation unit's late Holocene existence. The case for dependence upon the rocky scree/talus for moisture and fire protection extends to herbs, located between the rocks in preference to exposed soil adaptation (Malvaceae or *Hibiscus* being a prime example). The sheer numbers of *Thrichodesma* (Boraginaceae) in Figure 3 suggests species from this genus occupied most of the cracks and fissures across the rocky scree/talus and have maintained closest proximity to the rockshelter throughout the Holocene.

Later Holocene monsoonal vine-thicket and scrub development was accompanied by evidence for a progressive loss of Myrtaceae/*Eucalytpus* upper canopy cover on the lowland plain. From the mid-Holocene the open sclerophyll forest trended toward an open woodland formation and establishment in the late Holocene. Tree height would have reduced in response to decreasing environmental moisture with the canopy correspondingly irregular due to the wider spacing between trees (or possibly variable patchy nature in tree distribution). The mid- to late-Holocene woodland was not a tiered vegetation community as seen in the earlier open-forest. Understorey woodland components were equally scattered into patches that are widely spaced. The ground flora is also irregular in distribution and density. In composition, the open woodland did not incorporate broad-leaf, obligatory deciduous taxa nor fleshy-herbs, the penetration of light likely too high and too capable of invoking evaporative stress, especially under reduced and/or variable precipitation. The loss of such taxa may not have been absolute; as opposed to disappearing altogether the aforementioned

Erythrina, *Atalya*, *Cajanus,* Fabaceae, *Pandanus* and some herbaceous taxa may have contracted mid-Holocene to riverine and/or the rocky scree/talus. In replacement, the mid- to late-Holocene open woodland unit combines a more strictly sclerophyllous, xerophytic plant alliance, including Myrtaceae/*Eucalytpus*, *Grevillea, Adansonia*, Solanaceae and Poaceae species. The open woodland presented as fairly uniform. Whether this vegetation unit incorporated spatial diversity, with varied understorey presence/absence across wider lowland scales, is not able to be interpreted given the local nature of pollen deposition. The record as it stands reflects the immediate plain facing the northern orientation of the rockshelter. The same is true for the earlier Holocene open forest. It is possible the Napier Range itself may form a barrier, with pollen from the region to the south of the site potentially less likely to be incorporated.

Fire

Throughout the Holocene there was no obvious correlation between the pollen and microcharcoal results and so little can be concluded about the response of vegetation to fire as a form of disturbance or influence. This issue is further complicated by the dominant cultural archaeological sample sediment source. This outcome leaves many interesting questions unanswered and requiring additional research: Does fire benefit or disadvantage biodiversity? Is fire occurrence linked to vegetation biomass: does any link account for the XU61 charcoal record for example (increased biomass facilitating fire, but with the vegetation seemingly able to cope and maintain cover through burning episodes, something which may also suggest strong biodiversity)? How does burning affect understorey shrubs – does frequent burning result in their depletion? What is the occurrence of human-landscape fire with respect to human occupation of Carpenter's Gap 1?

Carpenter's Gap 1 botanical fossil-data comparison

Organic preservation through the excavated sediments has affected all botanic records. The strongest pollen preservation is consistent with highest observed abundances in other recovered plant remains as well as the largest number of cross-proxy species identifications.

The pollen evidence does not refute what is apparent from the macrobotanic, phytolith and wood-charcoal records regarding palaeoenvironments, recognizing also that little can be presented in this paper on the human exploitation of plants. The majority of pollen grains have entered and accumulated within Carpenter's Gap 1 as windborne particles, and are more akin to the phytolith record in providing an indication of changing Holocene environments than the macrobotanical and wood-charcoal records as representatives of plants selectively targeted in human use. The pollen can confirm the identification and timing of plant-food sources (*Terminalia, Vitex, Adansonia, Ficus*, for example) while also suggesting that such economically important genera were prevalent (or not) in

the landscape, a factor which may have influenced foraging distances. Carpenter's Gap 1, in the early-mid-Holocene landscape, supported higher biotic productivity comparted to the later Holocene, and much more than the vegetation of the onset of the LGM. The microcharcoal results do not correlate well with botanical remains nor archaeological artefact data leaving the relationship between human presence at Carpenter's Gap 1 and Holocene landscape burning unclear (as above). Based on phytolith evidence (Wallis, 2000), the retreat of the Arecaceae and their failure to re-colonise the area during and after the LGM, is due to aridity. Perhaps increased microcharcoal concentrations through this same period may also indicate inappropriately high fire regimes for this family. Sourcing areas of Arecaceae refugia within the Kimberley region, notably during climatic phases such as the LGM, would prove valuable in future research.

The pollen evidence adds weight to arguments for increased precipitation and therefore available environmental moisture during the Holocene, and can confirm the ongoing presence of monsoonal-forest as well as woodland associated flora within the vicinity of Carpenter's Gap 1 and probably the Napier Range more widely (consistent with similar study results from the more inland Riwi Cave, for example, Whitau et al., 2017). For the palaeoenvironment, and with the pollen results, more than one botanical proxy now demonstrates the Holocene site presence of Myrtaceae/Eucalytpus, Proteaceae/*Grevillea*, Combretaceae/*Terminalia*, Euphorbiaceae, Sapindaceae, Poaceae, *Adansonia*, *Ampelocissus*, *Ficus* and *Vitex* species. At the same time, previous botanical findings are able to narrow some of the plant identifications made via pollen and establish more specifically the composition of pollen-identified vegetation units. In example, identifications made as Sapindaceae are likely to include *Dodonaea*, and Euphorbiaceae likely to include *Petalostigma*. From the wood-charcoal data in particular (Frawley and O'Connor, 2010), the pollen-described open-forest and open-woodland canopies can be established more specifically as including one or a combination of *Eucalyptus bleeseri*, *E.camaldulensis*, *E.dendromerenix*, *E. polycarpa* and *E. tetradonta*.

An expansion in vegetative, ecological and climatic detail is considered to be the principal benefit gained from this paper. Specifically, pollen analysis has divided the last 11,200 years into two phases, in contrast to depictions of the Holocene as one time-block. A Holocene division has been hinted at previously, but not conclusively stated. Through an absence of macroscopic Cyperaceae remains McConnell and O'Connor (1997) suggested a dry phase during the recent Holocene. This was, however, argued by Wallis (2000) as indicative of changing human mobility and foraging strategies, rather than suggesting a decline in Cyperaceae growth through habitat reduction. The pollen results suggest a degree of both structural and compositional change in the Holocene vegetation surrounding Carpenter's Gap 1 extending to a degree of influential climatic variability. Monsoonal-forest and sclerophyll associated vegetation units changed between the early-mid-Holocene and mid-late

Holocene as the climate shifted from a more uniformly higher precipitation to a variable drier state. The vegetation and associated environments therefore cannot be simply described as the one vine-thicket ecology or the one *Eucalyptus* alliance for the duration of the Holocene. Such information has not been previously presented for Carpenter's Gap 1.

Carpenter's Gap 1 pollen results in a wider Kimberley context

A small number of local Western Australian studies may be found for comparison against the Carpenter's Gap 1 discussions in this paper. These studies are largely non-botanical and typically geomorphological or sedimentological in focus. This local situation is a general reflection of the status of palaeoenvironmental research in the wider northwest of Australia. This is a region often quoted as limited in opportunities due to a lack of natural deposits preserving long-term continuous botanics (e.g. Wallis, 2000, 2001; Whitau et al., 2017, 2018). Palynological records from marine-core sediments (Kershaw and van der Kaars, 2012; van der Kaars and DeDeckker, 2003; Wang et al., 1999) framed discussion on patterns of environmental change; however their data were very widespread in nature and while highlighting marked vegetation responses to glacial-interglacial cyclicity, the records are too coarse, are condensed, and their dating too uncertain to provide post-LGM and Holocene specifics. Such is the importance of Carpenter's Gap 1.

Questions surrounding vegetation dynamics/resources and human-environmental relationships aside (e.g. Veth et al., 2018), Holocene climatic stability, the onset timing of monsoonal regimes and their geographic extent are long-standing Quaternary research issues for northwestern Australia. Under a large precipitation gradient across the Kimberley today (BOM, 2019), weak monsoons are more likely to affect southern inland areas. Past monsoon tracking within desert dune formations across the Gregory Lake basin (Fitzsimmons et al., 2012; Reeves et al., 2013) and isotopic analyses of stalagmites (Denniston et al., 2013, 2015) constitute valuable early palaeoclimate references for comparison with the vegetation results in this study. Palynological research within the north Kimberley, including King River (Proske et al., 2014; 2015) and Black Springs (Field et al., 2017) provide more recent, albeit more distant, terrestrial comparisons.

Pre-47,000 yr BP, Gregory Lake conditions reflect a more effective monsoon and wetter climate (supporting vegetation biomass reflected in XU61). Dune activities under drier conditions *c.*35-12,000 yr BP, indicate lake regression and a monsoon that was either not active or did not penetrate as far south as today. The return of stronger monsoon systems delivering inland moisture has been dated from *c.*14,000 yr BP (Denniston et al., 2013; Fitzsimmons et al., 2012; Reeves et al., 2013). Jennings (1975) and Semeniuk (1980, 1982) illustrated a southwest Kimberley wetter-humid phase during the early to mid-Holocene (*c.*7000-6000 yr BP), coincident with closed monsoonal forest and sclerophyll

richness in the locality of Carpenter's Gap 1. Higher river sedimentary output is used to confirm intense wet seasons at this time, followed by records of site erosion as climates became drier. Wende et al. (1997) further described late Holocene declines in fluvial activity. McKenzie (1981), through sub-fossil fauna, also suggested a mid-Holocene period of increased rainfall but that ensuing drier climatic conditions resulted in localised southwest Kimberley extinctions (habitat loss). After the mid-Holocene (c.5000 yr BP) substantial dry dune re-activation took place in the Gregory Lake catchment (Fitzsimmons et al., 2012; Reeves et al., 2013). To the north, loss of organic content and/or stratigraphic absences, and reduction in aquatic plant species occurred (Field et al., 2017; Proske et al., 2014; 2015). North-east Kimberley palaeoecological studies (including pollen analysis) on three swamps presented notable variations in water levels during the late Holocene (from 2000 yr BP; Head and Fullager, 1992). These sites are used to suggest strong fluctuations in climate and environmental surface water availability. At Carpenter's Gap 1, the declines in broad-leaf evergreen plant cover as well as eucalypts, and reduction in vegetation complexities, can be correlated with such trends, however, late Holocene drying is not expected to have affected the northern Kimberley to the same extent as areas such as Carpenter's Gap 1, the latter more likely to incorporate later Holocene aridity.

The pollen findings from Carpenter's Gap 1 are not out-of-step with studies located elsewhere in the Kimberley, indicating a two-phased degree of Holocene climatic oscillation with variations in vegetation cover, both of consequence to Aboriginal occupants. This paper provides refinement of how changes in monsoonal regimes affected Carpenter's Gap 1 landscapes, describing the vegetation in close detail. Some southern Kimberley discrepancies remain, calling attention to the need for exploration targeting discovery of new sites and perhaps a reworking of data to settle debate (see Semeniuk, 1996 and Wallis, 2000 for arguments against Wyrwoll et al. 1986, 1992), thereby also refining our understandings of local to regional expressions of Kimberley and northwestern Australian change.

Importantly, the pollen data from Carpenter's Gap 1 are also more likely to reflect vegetation changes in the landscape of the site surrounds than the other proxy records from the site's macrobotanics, phytoliths and wood charcoal, which most likely derive from plants introduced into the site by people for food, combustion, shelter and/or the manufacture of items of material culture.

Conclusions

Plants have always been essential resources for people, and they are at the same time important indicators of ecological conditions. The pollen analysis presented in this paper now exists as part of a substantial and diverse set of reinforcing botanical data from Carpenter's Gap 1; data with the ability

to extend discussions and answer questions on past environments and human activities which cannot be answered by the archaeological record alone.

The new pollen results from Carpenter's Gap 1 provide a window into a dense mixed vegetation in the period of initial site occupation c.>45,000 yr BP. It also represents a continuous record of vegetation change from the beginning of the Holocene incorporating tree loss within a transition from monsoonal low closed-forest to vine-thicket and eucalypt open-forest to open-woodland. This vegetation transition centred on the mid-Holocene and suggests a shift in climate, becoming drier and more variable toward and into the late Holocene. Whether or not fire also played a role in the establishment of one vegetation unit over another at Carpenter's Gap 1 remains unknown.

Finally, caves and rockshelters frequently lie in physiographically different environments from lakes and swamps (Camacho et al., 2000). They provide valuable palaeoecological potential in this regard, however the interpretation of pollen assemblages should include consideration of how the pollen reaches and is incorporated into, as well as the differential preservation versus destruction properties, of such sites. For Carpenter's Gap 1 it is also recommended that off-site sampling options be explored. The interpretation of both regional to local palaeovegetation and palaeoclimate would be considerably strengthened with an additional source of data, and sampling away from direct human settlement loci is important to provide a record of landscape fire history.

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Figures and captions

Figure 1: Western Australia showing location of Carpenter's Gap 1, principle landscape features and other places mentioned in the text, with present-day rainfall isohyets (adapted from Dilkes-Hall et al., 2019).
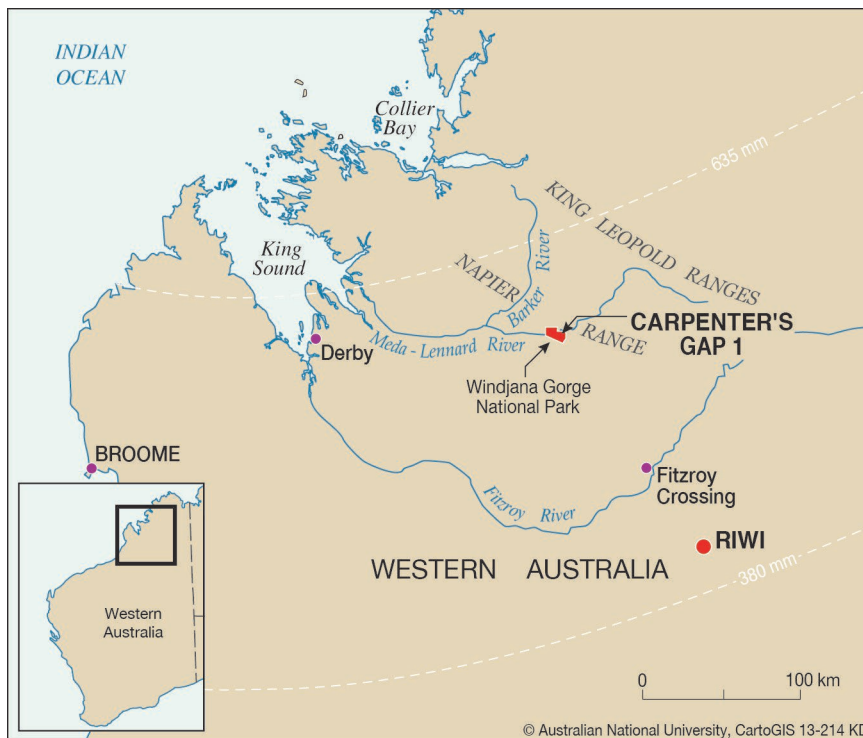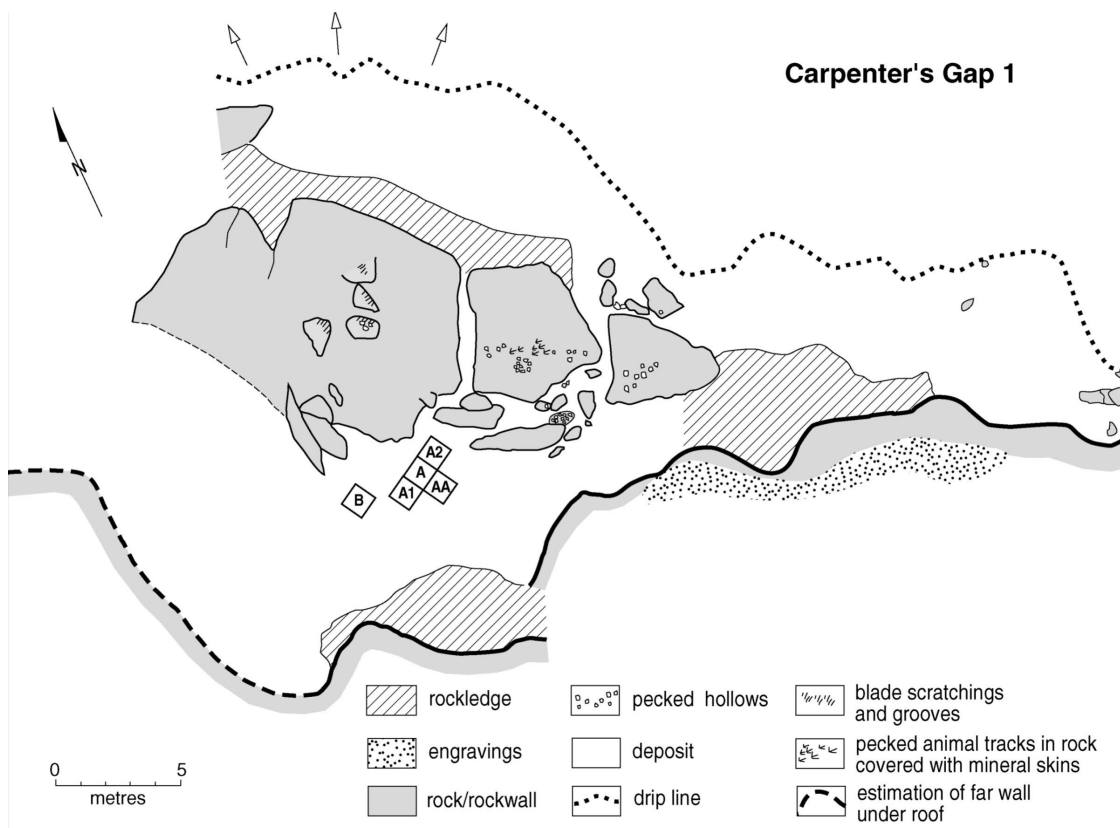
Figure 2: Carpenter's Gap 1. A) Photo showing approach to the site, facing south and B) site map showing location of excavation squares and surface topography (after Maloney et al., 2018).

Figure 3: Pollen (percentage) and microcharcoal (concentration) assemblage presented per excavation unit (XU), Carpenters Gap 1 (Square A2).
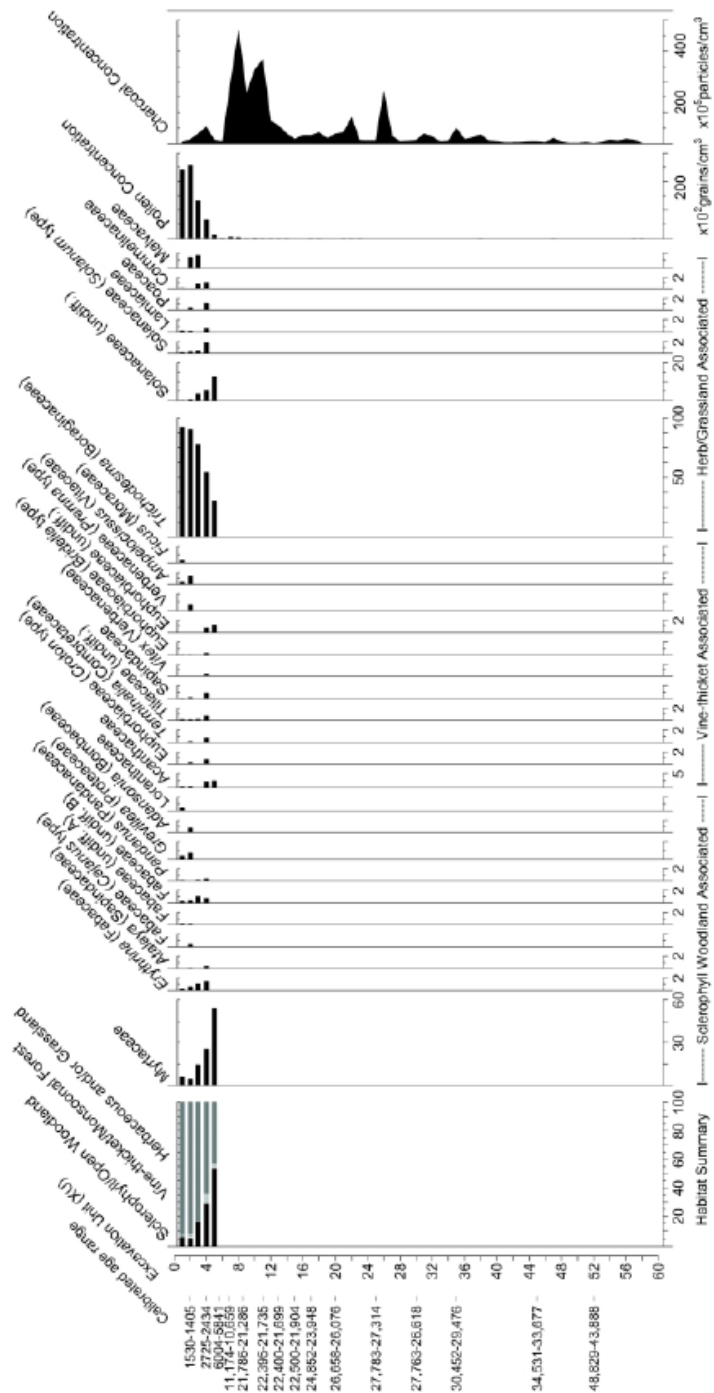
Figure 4: Undifferentiated and/or damaged pollen count per excavation unit (XU), Carpenter's Gap 1 (Square A2).
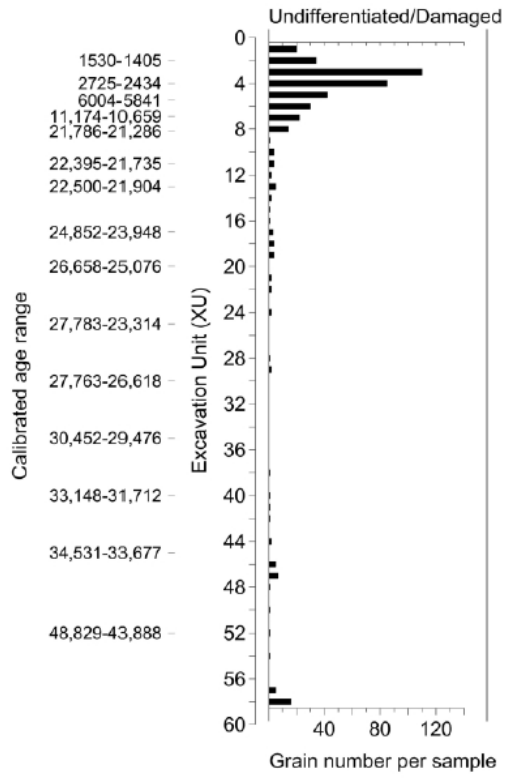
Figure 5: Pollen (percentage) and microcharcoal (concentration) assemblage from basal excavation unit (XU) 61, Carpenters Gap 1 (Square A2).
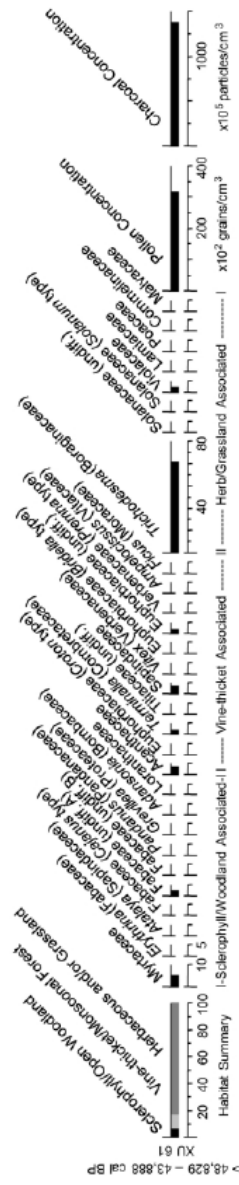
Table 1: Archaeological assemblage phases used to describe human occupation through time at Carpenter's Gap 1 (adapted from Maloney et al., 2018).

Archaeological Phase	Stratigraphic Unit	Excavation Unit	Age range (calibrated yr BP)	Site occupation interpretation summary
1	8	61 to 56	51,000-43,800 to 44,400-38,800	Early pulse of activity following initial settlement. Earliest tool technological activities.
2	7	55 to 35	41,400 - 36,00 to 30,300-27,100	Reduced site visitation. Discard rate of artefacts lower.
3	6	34 to 13	29,000-26,700 to 22,500-21,800	Periodic visitation throughout phase. No technological change; slight increase in artefact discard rate.
4	5	12 to 6b/6c	22,400-21,800 to 19,200-17,100	Spans the Last Glacial Maximum (LGM). Significantly increased site visitation. Largest artefact discard peak.
5	4	7 to 5a	18,600-8900 to 16,200-6500	Occupation represented by multiple complex SUs and difficult to document during this time (mobility and increased foraging range prosed).
6	3 to 1	5 to surface	7600-4900 to 700-300	High occupation signature. Shift in raw materials and foraging, to refocus on locally available resources.

Table 2: Radiocarbon sample results from Square A2, Carpenter's Gap 1 (adapted from Maloney et al., 2018; Frawley and O'Connor, 2010).

Laboratory Code	Stratigraphic Unit	Excavation Unit	Material	Recovery	^{14}C Age 1σ error (yr BP)	Calibrated age range 95.4% (cal BP)
Wk-37968	2	2	Charcoal	In situ	1611 ± 20	1530-1405
Wk-37970	2a	4	Charcoal	In situ	2527 ± 20	2725-2434
Wk-37969	2b	3	Charcoal	In situ	4059 ± 20	4533-4419 (92.9%)
ANU-11455	3	6	Charcoal	In situ	3900 ± 70	4442-4082 (92.8%)
Wk-19723	3	5	Charcoal	In situ	5204 ± 45	6004-5841 (73.5%)
ANU-11454	4	5a	Charcoal	In situ	7470 ± 70	8387-8152 (88.3%)
Wk-19724	4	7	Charcoal	In situ	7468 ± 51	8379-8160 (94.2%)
ANU-11450	4	7	Charcoal	In situ	9600 ± 80	11,174-10,659 (95.2%)
ANU-11456	5	6b	Charcoal	In situ	16,000 ± 710	21,261-17,812
ANU-11457	5	6c	Charcoal	In situ	17,130 ± 330	21,560-19,840
Wk-37971	5	8	Charcoal	In situ	17,814 ± 57	21,786-21,286
ANU-11459	5	9	Charcoal	Sieve	17,240 ± 130	21,129-20,397
ANU-11426	5	11	Charcoal	Sieve	18,240 ± 130	22,395-21,735
ANU-11427	6	13	Charcoal	Sieve	18,270 ± 160	22,440-21,699
ANU-11112	6	15	Charcoal	Sieve	18,430 ± 130	22,500-21,904
Wk-19725	6	17	Charcoal	Sieve	20,292 ± 150	24,852-23,948
Wk-37972	6	20	Charcoal	Sieve	22,192 ± 94	26,658-26,076
Wk-19726	6	25	Charcoal	Sieve	23,366 ± 150	27,783-27,314
ANU-11113	6	25	Charcoal	In situ	22,130 ± 200	26,658-25,992
ANU-11422	6	30	Charcoal	In situ	23,050 ± 300	27,763-26,618
Wk-37973	7	35	Charcoal	Sieve	25,791 ± 147	30,452-29,476

Wk-37974	7	40	Charcoal	Sieve	28,540 ± 203	33,148-31,712
Wk-37975	7	45	Charcoal	Sieve	30,022 ± 241	34,531-33,677
Wk-37976	7	52	Charcoal	Sieve	42,496 ± 1185	48,829-43,888
ANU-11425	8	56	Charcoal	Sieve	33,980 ± 790	40,245-36,372

Appendix A: Stratigraphic profile of Square A2 with radiocarbon samples plotted (after Maloney et al., 2018).
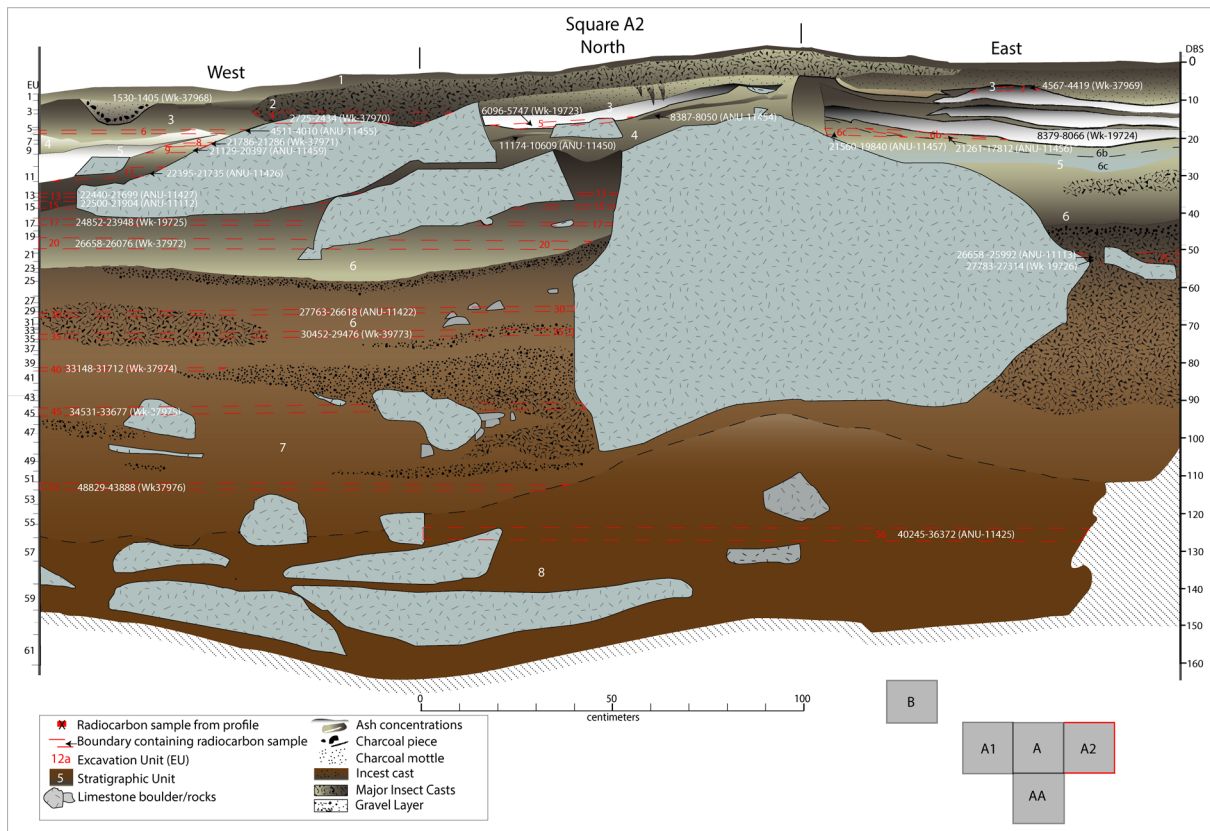
Appendix B: Ecological affiliation of pollen identified plant taxa, Carpenter's Gap 1 (Square A2).

Description, including ecological affiliation, of plant taxa as identified through pollen remains recovered from Carpenter's Gap 1 Square A2. In reference, Wheeler (1992), Western Australian Herbarium (1998), Brock (2001), Petheram and Kok (2003) and Moore (2005) have been used throughout. Plant taxa are presented in alphabetical order.

Acanthaceae (Juss.)

A predominantly tropical family consisting of shrubs or herbs (trees rarely, lianes few). Herbs may be annual or perennial. Dominated by plants that are hydrophytic (adapted to waterlogged soil or partly to wholly submerged in water), helophytic (with perennating buds situated in mud or water) or mesophytic (without adaption to environmental extremes; many in damp areas within tropical forest). Acanthaceae are rarely adapted to dry conditions that bring about excessive transpiration (xerophytic). The Kimberley region includes species from the following genera: *Acanthus, Thurnbergia, Staurogyne, Hygrophila, Brunoniella, Nelsonia, Rostellularia, Dicliptera* and *Hypoestes*.

Adansonia (Bombaceae) (L.)

Commonly known Boab. Conspicuously xerophytic. Trees, featuring enlarged trunk with branches radiating from the top. Deciduous, with prominent flowers appearing with/before new leaves during the early wet-season. Located amongst sandstone in dry regions; on slopes and ridges on sandy soils, on sand-plains and associated with drainage lines or watercourses. Seeds and pith from the fruits may be eaten. *Adansonia gregorii* is located within the Kimberley.

Ampelocissus (Vitaceae) (Planch.)

A genus composed of lianes (in majority), shrubs, herbs or herbaceous climbers; growth extending from perennial tubers. Evergreen, with very small (although numerous) flowers, and globular/fleshy berries produced late in the wet-season. Plants can be mesophytic or xerophytic. *Ampelocissus acetosa* occurs through the Kimberley, common in sandstone woodland or shrubland; also monsoon forest associated including drier vine-thicket on sandstone hills or rocky outcrops. Berries may be eaten raw.

Atalaya (Sapindaceae) (Blume.)

Trees or shrubs, slender in appearance. Evergreen, producing flowers and fruit in the late dry-season; white flowers are profusely produced along dense (clustered) heads. Widespread Kimberley distribution through open forest and woodland on a variety of soils also extending into savanna woodland or grassland in dry regions; recorded species are *A. variifolia, A. hemiglauca* and *A. salicifolia*.

Bridelia (Euphorbiaceae) (Willd.)

Small trees or shrubs, semi-deciduous in habit and featuring inconspicuous green-white flowers developing into dark globular fruit in the early to mid dry-season. Plants are mesophytic trending to xerophytic. Represented in the Kimberley by a single species, *Bridelia tomentosa*; widespread, occurring on sandstone or basaltic soils and frequently in vine-thicket or low-closed monsoonal forest. Fruit may be eaten.

Cajanus (Fabaceae) (DC.)

A genus of shrubs or herbs (shrubs or perennial herbs with annual climbing or prostrate stems; rarely actual lianes). Evergreen and resinous. Flowers occur in racemes of 4-10, single in axils. Ten species occur in the Kimberley with *C. lanceolatus* and *C. viscous* endemic to the region. Occurs predominantly in open habitats, including woodland and grassland on sandstone and limestone.

Commelinaceae (Mirb.)

A (sub)tropical family of herbs or herbaceous climbers, predominantly perennial. Plants are evergreen and may be succulent, producing flowers aggregated into inflorescences. Typically helophytic or mesophytic. The Kimberley includes species from the genera *Cartonema, Murdannia, Cyanotis* and *Commelina*.

Croton (Euphorbiaceae) (L.)

Croton comprises trees or shrubs but rarely herbs. Some species are deciduous and flowers are inconspicuous but appear in slender racemes. Plants are mesophytic trending to xerophytic. Moore (2005) notes that *Croton*, although a northern monsoonal forest plant, appears to be extending its range southward into semi-arid, sandy regions. The species *C. argyratus*, *C. habrophyllus* and *C. tomentallus* occur in the Kimberley, in vine-thickets but also recorded in shrubland across gravelly-ridges and rocky hillsides.

Erythrina (Fabaceae) (L.)

Erythrina form slender trees, deciduous in habit and usually leafless at the time of flowering (late dry-season). Prominent red pea-flowers form on dense racemes. Plants are xerophytic and occur amid open-forest and woodland on a variety of well-drained soils and often on shallow gravelly soils, extending into savanna or shrubland. A genus represented in the Kimberley by a single species, *E. vespertilio*, commonly known as the Coral tree.

Euphorbiaceae (Juss.)

A family cosmopolitan in distribution but particularly abundant in tropical regions. Varied in habit, existing as trees, shrubs, herbs (or herbaceous climbers) and lianes. Euphorbiaceae is found as a component of a wide variety of habitats and Wheeler (1992) describes the 27 genera and associated species recorded across the Kimberley.

Fabaceae (Lindl.)

The 'Flora of Australia' series defines Fabaceae (commonly the 'peas') as the third largest in Australia and Wheeler (1992) describes the Kimberley region's 64 genera and species therein. The Fabaceae are a family of trees, shrubs or herbs, with stem features including spines and phylloclade formation. The inflorescences occur in racemes, spikes or heads and are only occasionally solitary. Moore (2005) outlines Fabaceae as consisting of pioneers, among the first to germinate after fire/disturbance and notes that long-lived perennial behaviour is rare. Fabaceae ecologically serve to convert atmospheric nitrogen into nitrogenous soil compounds able to be utilised by other plants. Seeds form an important food source.

Ficus (Moraceae) (L.)

The 'figs'; trees, shrubs or lianes (climbers or epiphytic stranglers). Evergreen as well as deciduous in habit with inflorescence of few to numerous flowers enclosed in the fruit (fused receptacle). Habitats incorporate monsoon forest associated with permanent lowland freshwater streams, drier vine-thickets on sandstone hills, woodland shrubland understorey and rocky outcrops in woodland, cliff-faces and rock crevices. Thirteen species are widespread through the Kimberley region (see Wheeler, 1992). Fruit may be eaten.

Grevillea (Proteaceae) (Knight).

A large genus (23 Kimberley species) of prostrate evergreen shrubs to small trees. Distinctive leaf-blade and floral formations; typically prickly-toothed (dentate) divided leaves with green-cream to yellow-orange flowers in slender pendulous racemes. Significantly xerophytic (often found in close association with *Eucalyptus*); inhabits open woodland and sparse shrublands in dry regions, on slopes and low stony ridges in sandy or stoney soils, sandstone areas on slopes and stony outwashes.

Lamiaceae (Martinov.)

A cosmopolitan family consisting in the majority of herbs (annual and perennial). Plants may be helophytic or mesophytic. More infrequently Lamiacese are xerophytic. The Kimberley region includes species from the following genera: *Pogostemon, Anisomeles, Plechtranthus, Solenostemon* and *Basilicum*. Alien species from *Hyptis* and *Ocimum* also occur.

Loranthaceae (Juss.)

Commonly known as mistletoe and typically bird-pollinated (flowers typically paired, often large and showy). The mistletoes are semi-parasitic 'shrublets', are evergreen and xerophytic. Species of *Dendrophtoe, Lysiana, Decasisnina, Diplatia* and *Amyema* occur in the Kimberley, located in open vegetation communities and are host-restricted – associated with *Acacia, Casuarina, Eucalytpus, Bauhinia, Melaleuca* and *Dendrophthoe*.

Malvaceae

A family of tropical and warm-temperate species comprised of herbs, shrubs and less commonly trees. Herbs may be annual or perennial. Flowers are often large and showy, particularly when solitary. Plants are helophytic or mesophytic (the herbaceous tendencies often appear soft and 'fleshy'). Fourteen genera occur in the Kimberley, with *Hibiscus* and *Sida* notably diverse. The herbaceous Malvaceae can be known as invaders of disturbed ground.

Myrtaceae (Juss.)

An evergreen tree and shrub family with significant presence in the Kimberley and including abundant *Eucalyptus* species as well *Osbornia, Myrtella, Eugenia, Syzygium, Xanthostemon, Melaleuca, Lophostemon, Leptospermum, Verticordia, Calytrix* and *Homalocalyx*. The Myrtaceae occupy essentially all Kimberley habitats.

Pandanus (Pandanaceae) (L.f.)

A genus of terrestrial, semi-aquatic or occasionally epiphytic trees or shrubs, often with aerial or prop roots with well-developed cap-roots. Branching habit can be horizontal and leaves are clustered spirally toward the end of each branch. Flowers are aggregated in inflorescence; in spikes or heads. Fruit is fibrous and woody, often wedge-shaped. Commonly associated with lowland watercourses, swamps (and the like) and the fringes of floodplains where species can form large stands. Also inhabits open forest and woodland, dissected outcrops and rocky-crevices. Six species of *Pandanus* occur in the Kimberley.

Poaceae (Barnhart & Barnh.)

The 'grasses' and occasionally referred to as Graminaceae. A large family of annual or perennial herbs, tuffed, rhizomatous, stems erect, prostrate or creeping, (un)branched at base or less commonly aerially. Leaves typically described as 'blades' and the inflorescence features as 'spikes'. Wheeler (1992) includes a classification of Poaceae in the Kimberly region, providing an identification key to the 82 genera of the region.

Premna (Verbenaceae)

Evergreen small trees or spreading undershrubs. Plants feature broad and ovate to round leaves with much-branched terminal inflorescences and small globular fruit; flowers and fruit tend to occur at the same time. Widespread in the Kimberley, commonly in forest or vine-thicket. Three species are recorded: *P. heracea, P. acuminate* and *P. serratifolia*.

Sapindaceae

A family concentrated in the (sub)tropics and comprised of trees or shrubs, occasionally lianes but rarely herbs. Plants from the family are overall mesophytic (many associated with vine-thicket and riverine vegetation communities) but can tolerate drier classification extremes and extend into woodlands, *Dodonaea* as example. The Kimberley incorporates species from the genera *Atalaya, Distichostemon, Dodonaea, Alectrypon, Ganophyllum, Cupaniopsis*, and *Lepisanthes*.

Solanum (Solanaceae) (L.)

Commonly known as the Bush Tomato or Bush Potato. Annual or perennial herbs (also herbaceous climbers) as well as shrubs. Plants are evergreen, with densely hairy to velvety leaves. Inflorescence are commonly terminal and solitary (purple). *Solanum* species trend toward being xerophytic and occur across sandstone, on stony slopes and amongst rocky outcrops (extending into woodland understorey) in the Kimberley (17 species recorded in the region).

Solanaceae (Juss.)

A family widely distributed in tropical and warm-temperate regions. The Solanaceae comprise herbs, shrubs, small-trees and lianes (commonly known to be 'prickly'). Herbs may be annual, biennial or perennial with family tolerances ranging between helophytic to xerophytic. The genera *Nicotiana, Duboisia, Solanum*, and *Physalia* occur in the Kimberley region; the genera *Lycopersicon* and *Datura* occur as alien genera.

Terminalia (Combretaceae) (L.)

A genus of spreading trees and shrub (commonly known as the wild-plums), typically (semi)deciduous. Plants feature rough bark, narrow pendulous leaves and showy green-cream flower spikes. A common understorey genus in open-forest and woodland, growing on a wide variety of well-drained soils. *Terminalia* is also associated with lowland freshwater (permanent or seasonal) streams and monsoonal forest (including here as a canopy emergent). Twelve species occur across the Kimberley region. The woody fruits can be eaten

Trichodesma (Boraginaceae) (R.Br.)

Coarse annual or perennial erect herbs or small shrubs. Pale, narrow ovate leaves and with numerous pendulous inflorescence. Widespread in the Kimberley region, especially in the southern half. Plant

habitat incorporates open woodland and sparse savanna woodland/grassland, extending to dry regions; sandstone areas on rocky slopes. May be a coloniser of degraded/disturbed ground. *Trichodesma* in the Kimberley is represented by a single species, *T. zeylanicum* (commonly known as Camel Bush)

Violaceae

A cosmopolitan family comprised of annual or perennial herbs or shrubs and only rarely trees (small). Violaceae is represented in the Kimberley by only one genus, *Hybanthus*.

Vitex (Verbenaceae) (L.)

Trees or shrubs with a (semi)deciduous habit under high water-stress. Plants feature tri-foliate leaves, the elongated leaflets with fine-pointed tips. The genus is further distinguished through its blue-purple orchid-like flowers and dark fruit. Habitats include monsoonal vine-thicket positioned in gullies or on sandstone hills or rocky-outcrops in woodland. Five species are recorded in the Kimberley region; with Wheeler (1992) suggesting *V. velutinfolia* is endemic and commonly associates with *Adansonia gregorii.* Fruit may be eaten.

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