Landscape Change and Indigenous Fire Use in the Namadgi Ranges in the Australian Alps over 16,000 years

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We assemble an environmental history for three *Carex gaudichaudiania* fens in the Namadgi Ranges in southeastern Australia through a multi-proxy approach focusing on macrocharcoal and geochemical X-ray fluorescence (XRF) core. Sediment accumulation commenced from 16 ka, following alpine deglaciation and climatic amelioration. The landscape of the terminal Pleistocene, with establishing wetland and forest vegetation interspersed by frequent catchment instability, transitioned to a relatively stable and productive early Holocene environment, from 11.5 – 9 ka, associated with an increased fire frequency. From 9 ka, alternating cycles of detrital influx and organic productivity, with possible gaps in the sediment records, attest to a renewed period of landscape instability, which continued past the mid Holocene *Pomaderris* phase of Martin (1986). Rapid peat accumulation commenced from 3.4 ka, as did an increase in fire. Through the comparison of the environmental data to local archaeological records, we propose a variable Aboriginal contribution to catchment-specific fire activity during three distinct periods, that is between 8 and 5 ka, between 5 and 3.5 ka, including the utilisation of Nursery Swamp itself around 4ka, and from 2 ka until European occupation.

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KEYWORDS: archaeology, Australian Alps, climate change, fire history, sedge fen.

INTRODUCTION

Peatlands preserve their histories in accumulating peat layers, capturing records of local events such as fires and catchment erosion, and evidence for broader trends such as changing organic productivity, vegetation and climate regimes. The peatlands of the northern Australian Alps have been studied for a long time, notably Costin (1954), a survey of ecology and soils of the Monaro, Helman and Gilmour (1985), an ecological study of mires above 1000 m in the Australian Capital Territory (ACT), and studies of the palaeoecology and chronology of peatlands (Hope 2003, 2006; Hope and Clark 2008; Kemp and Hope 2014; Zheng et al. 2019). The Peatland Project has also resulted in the mapping of significant peat-forming mires of the ACT (Hope and Southern 1983; Hope et al. 2009; 2012) including records of recent changes in vegetation and hydrology (Whinam et al. 2010).

This study has sought to improve the understanding of landscapes, climate, fire regimes and human occupation of the Namadgi Ranges, which are situated in the most northeasterly part of the Australian Alps, after the Last Glacial Maximum (LGM). We describe the environmental histories of three sedge fens from adjacent valleys, Nursery Swamp, Bogong Creek Swamp and Boboyan Swamp, using environmental proxies, including macroscopic charcoal particles and geochemical core profiling, and compare the data with the archaeological record.

The research has interpolated the Namadgi landscape histories and the archaeological chronology of the high country spanning the Holocene (Theden-Ringl 2016, 2017), and detects a variable anthropogenic fire signal in the palaeoenvironmental record. Fire is a dominant feature of the Australian environment, and has been shown to have varied temporally and regionally in association with major climatic changes such as glacial periods and arid phases (Lynch et al. 2007), in response to factors including fuel availability, effective precipitation, vegetation change, and also to the activities of people. Fires and burning are fundamental components of Aboriginal land management, and the question of whether evidence of human fire regimes can be detected in the palaeoenvironmental record has been discussed for many decades (Tindale 1959; Jones 1969; Gill 1977; McBryde and Nicholson 1978; Singh et al. 1981; Horton 1982).

In recent years, the compilation and analysis of broad-scale fire and archaeological datasets has become commonplace. These include continent- and subcontinent-wide studies (Power et al. 2010; Mooney et al. 2011; Bird et al. 2013; Williams et al. 2015), none of which detected significant correlations between archaeological evidence of human activity and the history of biomass burning as inferred from charcoal records. While regional compilations may suffer from generalised assumptions of both human and environmental shifts through time, only a small number of studies have attempted to directly correlate archaeological and palaeoecological data at more localised scales (Clark 1973; Hope 1978; Ellis and Thomas 1988; Head 1989; Black and Mooney 2006; Black et al. 2007; Mooney et al. 2007; 2020; McWethy et al. 2017; Romano and Fletcher 2018). Some of these studies have reported changes in fire regimes or vegetation communities that correlated with archaeological presence or with potential burning activities by people (Clark 1973; Hope 1978; McWethy et al. 2017; Romano and Fletcher 2018; Mooney et al. 2020). The impacts of human occupation have often proven to be invisible against change driven by natural climate change and variability (Mooney et al. 2011). Despite this masking Constantine et al. (2023) found that Indigenous peoples have been undertaking cultural burning in Australia since the beginning of the Holocene, acknowledging that anthropogenic fire regimes have certainly contributed to the fire history of the continent.

Gammage (2012) and Pascoe (2014), present provocative arguments that sophisticated and complex land management techniques employed over millennia by Aboriginal people contributed to significant landscape changes, especially with the use of fire, and hence the magnitude and visibility of such impacts remains enigmatic. By directly comparing catchment-specific palaeoenvironmental and archaeological datasets, this study provides a highly localised approach to the question.

Geographic, scientific and archaeological context

The Namadgi Ranges, with elevations from around 900 to over 1900 metres above sea level, are part of the Australian Alps that extend northwards from Victoria. The Namadgi ranges are deeply dissected on their eastern side by large open valleys, and their geology is dominated by Upper Silurian Shannons Flat Granodiorite of the Wyangla Supersuite (Geoscience Australia and Australian Stratigraphy Commission 2017). The catchments have a trellis drainage pattern with an NW-SE orientation and are tributaries of the upper Murrumbidgee River (Figure 1).

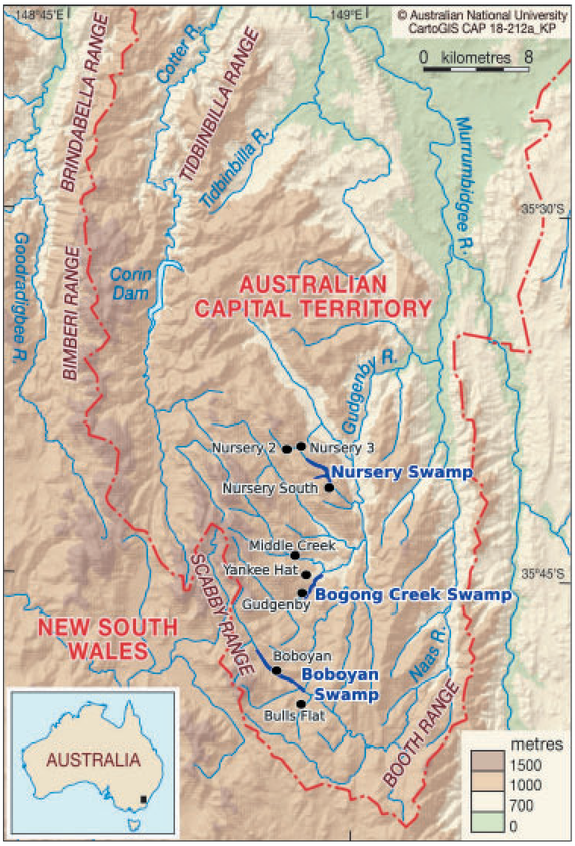

Figure 1. Map showing location of studied peat deposits (blue) and archaeological sites (black).

The morphologies of Nursery Swamp, Bogong Creek Swamp and Boboyan Swamp are similar. They are sedge fens located at approximately the same altitude but in separate valleys within 20 km of each other, and experience similar climatic environments. Their mean annual temperatures were modelled using BIOCLIM (Busby 1991), as 10.1°C – 10.2°C, but these valley bottoms are extreme frost hollows in winter. The modelled average annual rainfall is 830 mm – 840 mm. All have montane ecologies, with the catchment slopes dominated by an open forest of mountain gum, *Eucalyptus dalrympleana*, with alpine ash, *Eucalyptus delegatensis*, and manna gum, *Eucalyptus viminalis*, forest on south facing slopes. Woodland on the higher slopes consists of snow gum, *Eucalyptus pauciflora*. The valley-bottom and lower slopes support grasslands of *Poa* and *Danthonia* spp. with scattered candle barks, *Eucalyptus rubida*, and black sallees, *Eucalyptus stellulata*. Severe frosts limit tree growth in the grasslands and produce an inverted treeline around the valley edges. The cool temperatures and waterlogging result in peat-forming topogenous sedge fens in the valley bottoms (Figure 2).

The fens themselves are elongate valley-fill peat deposits, with two to three metres of less humified fibrous peat over deeper layers of humified peat and peaty clays, in places accumulating more than five metres of sediment (Table 1). Coarse sands and gravels often underlie the fens; and these are a source of groundwater that helps maintain them. The dominant vegetation is *Carex gaudichaudiana*. Although none of the fens has an incised channel, with water spreading across the swamp surface, Boboyan Swamp contains several vague linear channels, as well as remnants of wooden posts suggesting livestock grazing and yarding occurring directly on the swamp surface. Sections of this peatland are likely to have been ditched during the past century of grazing to promote grass growth and more solid footing for livestock. This appears to have impacted the organic content of the top layers of this core, where there is some sediment loss due to oxidation of peats, an assertion which is supported by the geochemical data.

Prior to obtaining National Park status in 1984, and dating from the start European settlement of the area in the 1830’s, practices of extensive grazing, tree clearing and frequent burning resulted in soil erosion, shrub invasion and widespread overstorey degradation in the *E. pauciflora* woodland (Keaney 2016). Feral animals including pigs, deer, horses and rabbits still occur in the catchments. Severe bushfires in 2003 and 2020 burnt Nursery Swamp and its catchment. Sedges re-sprouted in the fen within a few weeks, with a discernible change being a debris raft of charcoal. This recovery indicates that healthy sedge fens are resistant to fire damage and recover quickly, with little damage to the peat (French et al. 2016). It should, however be noted that sediments in drained peatlands are much more susceptible to organic loss from fire, and many organic soils can become combustible at some time each summer (Prior et al. 2020).

Several Aboriginal groups have long-term connections to the Namadgi region, reflecting the diversity and interconnection of groups with ties to

Figure 2. View of Boboyan Swamp (photograph by B. Keaney).

	Nursery Swamp	**Bogong Creek Swamp**	**Boboyan Swamp**
Altitude	1092 m	1000 m	1154 m
Swamp location	35°40.59'S, 148°58.31'E,	35°45.38'S, 148°57.82'E	35°48.92'S 148°56.03'E
Geography	Elongate valley fill occupying a narrow valley between granitic ridges on a SE flowing tributary stream that rises on Mt Orroral (1608 m) and falls to the Gudgenby River.	Elongate valley fill formed on a gently sloping bench in jointed granodiorite, surrounded by slope fans from steep ridges. Part of Bogong Creek, which rises on Mt Gudgenby (1739 m).	Elongate valley fill formed on a gently sloping bench in jointed granodiorite, surrounded by slope fans from steep ridges. Part of the upper Naas River, which rises on Mt Gudgenby (1739 m).
Catchment size	~680 ha	~1450 ha	1640 ha
Swamp size	26 ha 3.7 km length in several connected basins	35 ha 2.5 km length in several connected basins	34.5 ha 3.6 km length and 50-100 m wide.

Table 1. Information on the three investigated peat deposits

the 'high' country. They include the Wiradjuri of the South Western slopes, the Walgalu of the high country west of the Murrumbidgee, the Ngunawal of the Southern Tablelands, the Ngambri of the Canberra region, and the Ngarigo of the Snowy Mountains and Monaro Tablelands (Howitt 1904; Tindale 1974; Wesson 2000; Flood 2010). Archaeological work has refined the chronological framework of human habitation in the Namadgi Ranges through the Holocene (Theden-Ringl 2016, 2017), with Aboriginal presence also previously established to at least c. 25 ka in the Namadgi foothills (Flood et al. 1987). Eight rock shelter sites with dated archaeological deposits occur within the three studied catchments. They are spatially situated from immediately adjacent to a fen to within three kilometres distance. Consequently, the archaeological and palaeoenvironmental records can be compared at a catchment-specific level. The sites have been described in detail elsewhere (Flood 1980; Rosenfeld et al. 1983; Theden-Ringl 2016, 2017) and form the chronological basis on which the local archaeological record is centred (Figure 3).

METHODS

Coring and core chronology

Duplicate cores were extracted in 50 cm increments from three peat deposits at Nursery Swamp (NUS-15), Bogong Creek Swamp (BCC-13) and Boboyan Swamp (BOB-14) using a Russian D-section corer; a Livingstone corer was employed where firm basal clays were reached. The cores were photographed and packaged in plastic sleeves in the field, then stored under refrigerated conditions. Of each duplicate set of cores, one was sub-sampled at 1 cm intervals for destructive sampling and the other was retained intact for non-destructive analysis. Core stratigraphy was described using a modified version of the Troels-Smith method (Kershaw 1997).

Dating is based on 29 AMS radiocarbon dates (11 from NUS-15, nine from BCC-13 and nine from BOB-14), from charcoal pieces in sieved fractions (and additional organic material or bulk samples in some cases, see Suppl. Information). Accelerated Mass Spectroscopy (AMS) dating of samples, pre-treated by author GSH using standard acid-base-acid treatment (Olsson 1986), was conducted at Direct AMS Radiocarbon Dating. The modern dates for depths at which *Pinus* pollen consistently appears in each swamp sequence and indicate post-European settlement is estimated at between 1880-1910 when there was widespread homestead plantings of pines, and complement the radiocarbon dates for age-depth modelling. Core chronologies were constructed using the age-depth modelling program 'Bacon v2.2' (Blaauw and Christen 2011; R Development Core Team 2015: Fig. 2), using the SHCal13 ^{14}C calibration curve (Hogg et al. 2013).

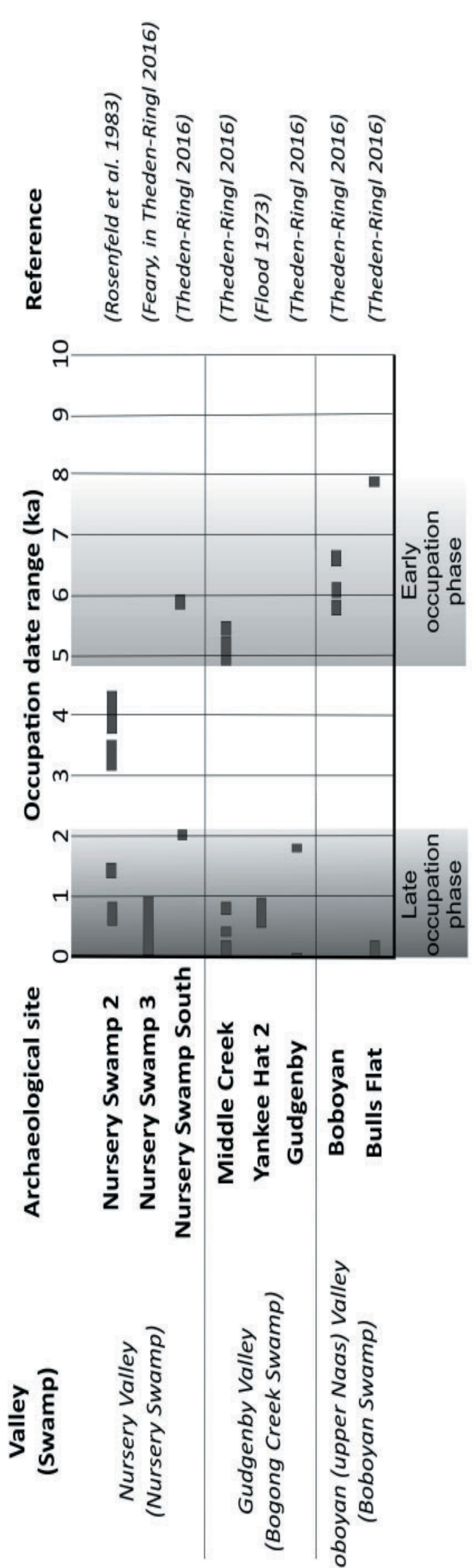

Figure 3. Timeline of occupation records for dated archaeological sites associated with Namadgi Swamps

Geochemical profiling and analysis

A Cox Analytical Itrax µXRF core scanner based at the Australian Nuclear Science and Technology Organisation (ANSTO) incrementally scanned the surface of each core section with a step size of 1 mm, using a 3 kW molybdenum tube set at 30 kV and 55 mA with a dwell time of 10 seconds. A chromium tube was used for NUS-15. Itrax element data is semi-quantitative, with count rates recorded for elements in cps (counts per second) previously established to be proportional to concentrations in fine-grained samples (Croudace et al. 2006). The scanner also recorded magnetic susceptibility (κ) in 5 mm increments. (κ) is an indicator of terrigenous sediment fluxes, particularly as a rainfall and run-off proxy (Rothwell and Croudace 2015). Where data at the ends of each segment gave low cps readings these were removed, hence short gaps in data are evident in the results. For geochemical data obtained for 25 elements across all cores, a first order normalisation of raw peak area data by total count rate for each depth interval was undertaken to account for potential core surface inconsistences. Pearson correlation coefficient analysis and principal component analysis (PCA) were used to identify and visualise associations between normalised element data.

Organic content cannot be detected directly using the Itrax, but as organic carbon has a lower average atomic mass than carbonates, aluminosilicates, or silica, the ratio between incoherent and coherent scatter (Inc/Coh) of the Itrax tube anode increases with greater organic carbon concentrations (Burnett et al. 2011). The Inc/Coh ratio can thus be used as a qualitative proxy for organic content (Jarvis 2012). In turn, organic content may have a ‘diluting’ effect on the Itrax data, lowering counts for detected elements and masking variations in other components (Ziegler et al. 2009; Lowemark et al. 2011). Comparison of the normalised element data, and element data further compared against Inc/Coh, shows that our data are not notably affected. Nonetheless, the use of element log-ratios counters any potential dilution effect, as ratios are insensitive to dilution by other sediment constituents that might introduce variations in absolute peak areas (Croudace et al. 2006).

Charcoal analysis

Sediment samples of 1 cm^3 were extracted from 1 cm core intervals. Samples were digested in bleach (sodium hypochlorite 15g/L) and gently rinsed with water through 250 and 125 µm sieves. Carbonised particles of each size fraction were counted manually under a stereomicroscope at 1 cm resolution, and at 2 cm resolution in several sections with consistently low count averages. Macrocharoal values were analysed with CharAnalysis (Higuera et al. 2009), which utilises non-influx count data (particles/cm^3) and the age-depth model from each core to derive charcoal accumulation. A calculated background charcoal (CHAR$_{back}$) component using a Lowess smoother and 95% peak identification was used to identify significant charcoal peaks assumed to reflect local catchment fire events. Settings were selected for optimal signal to noise index, with a locally defined threshold and no specified zones.

RESULTS

Core chronology

Figure 4 shows age-depth models for all cores, indicating that sediment accumulation rates varied through time and between sites. Main graphs show calibrated ^{14}C dates and age-depth models, 95% confidence intervals and single 'best' model based on weighted mean age for each depth.

The Nursery core NUS-15, has relatively good representation of sediments from ca 14 ka to just after 9 ka (Figure 5). The lowest units, representing the terminal Pleistocene to 11.3 ka, consist of clays with varying sand and gravel, overlying dense basal sands and gravels. The early Holocene (ca 11.3 to 8 ka) is represented by compact fibrous peat with a variable clay component, forming clay bands in several sections. Above a mid Holocene section that has poor chronological control, and is paled out in the Figure, the mid to late Holocene record starts just prior to 5 ka, and is characterised by significant changes in all proxies, including an accelerated growth rate of sedge peat from ca 3 ka.

The core from Bogong Swamp, BCC-13, appears to have a relatively complete peat column from around 7 ka to the present, but the chronology prior to this is less well established (Figure 6). The lowest section, comprised of dark brown silty sand, may represent sedimentation prior to 16 ka. Dates from the grey sandy silts that comprise the lowest metre indicate relatively slow and/or sporadic sedimentation from the late Pleistocene through to the early Holocene. The core section dating to the mid Holocene, where the core chronology becomes better established, comprises bands of organic-rich clay and silt interspersed by layers with varying sand and gravel components. Fibrous peats appeared in the core shortly after 4 ka, becoming the dominant component from ca 3.4 ka.

The Boboyan core, BOB-14, has poor chronological control prior to 9 ka but improves considerably from just after 9 ka to the present (Figure 7). The lowest metre of sediment,

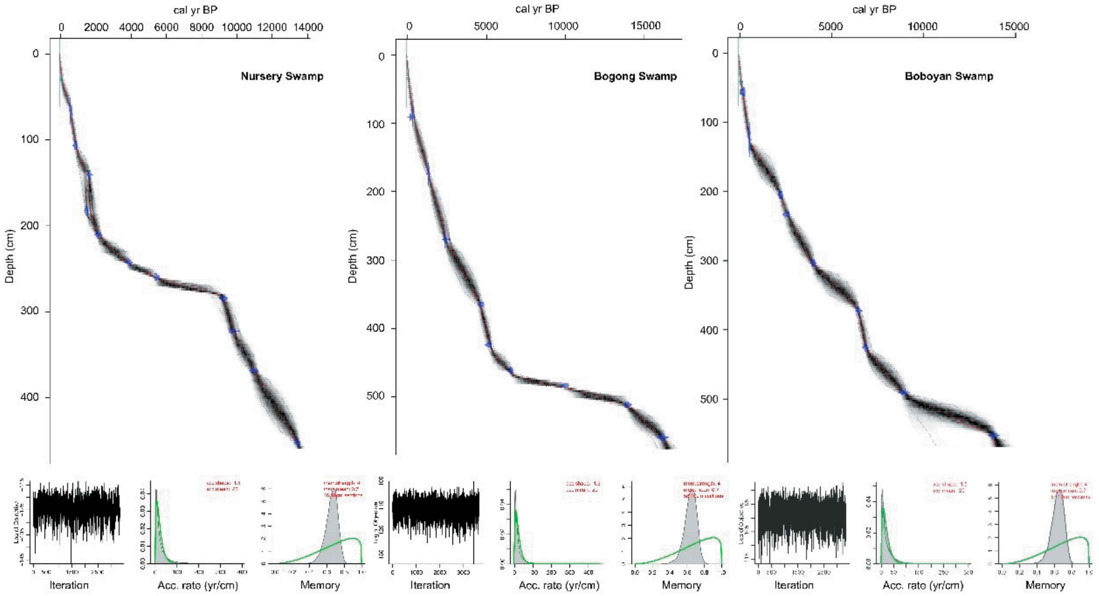

Figure 4. Age-depth models for Nursery, Bogong and Boboyan Swamps, constructed with Bayesian modelling software Bacon 2.2. Plots at bottom of figure show, left: stability of model; middle: prior and posterior distributions of accumulation rate; and right: prior and posterior distributions of memory properties.

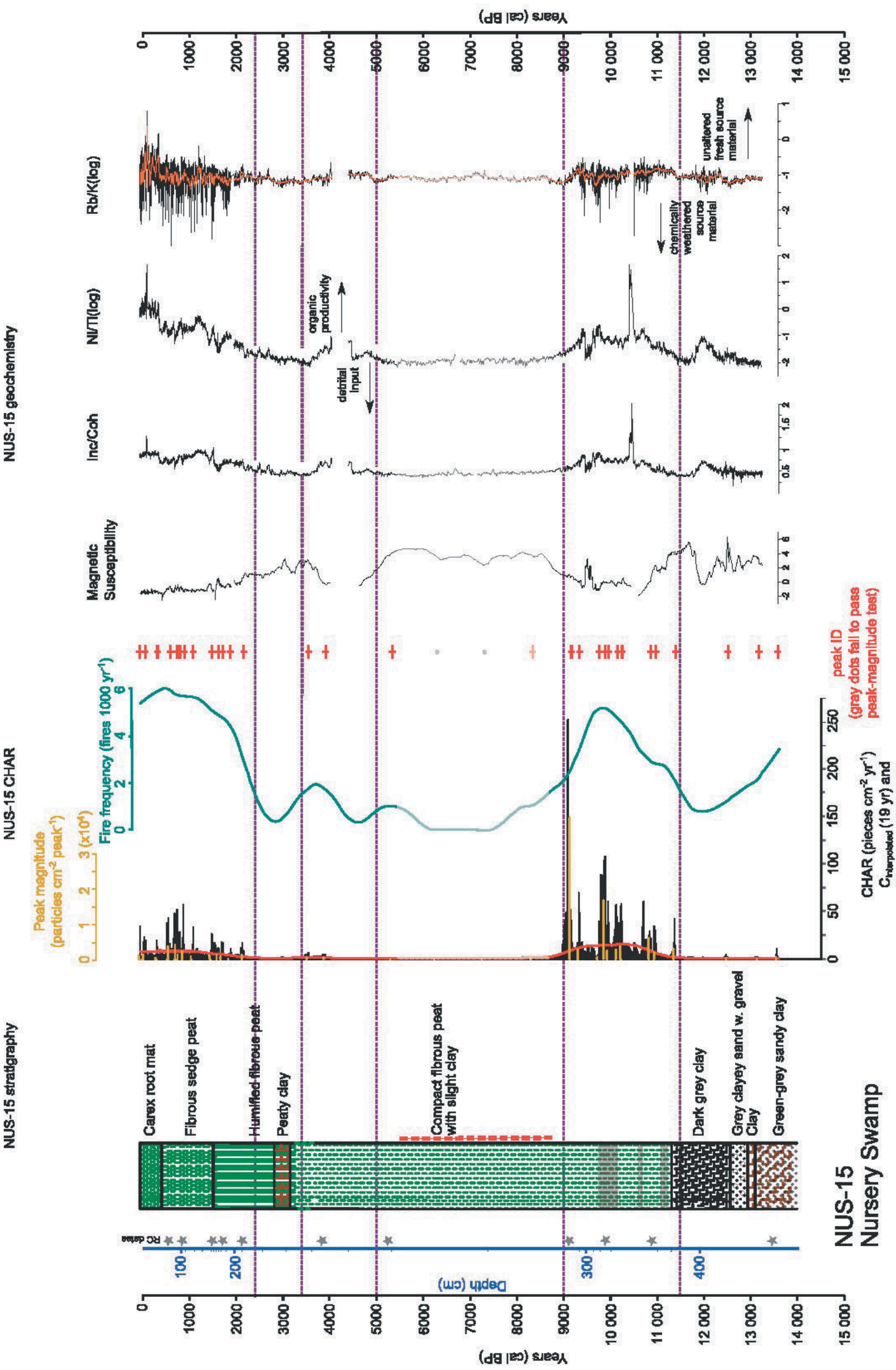

Figure 5. Summary of results from NUS-15. Fire history based on CharAnalysis (Higuera et al. 2009); vertical red dotted line and paled sections indicate poor chronological control; major chronological phases indicated. The orange line in the Rb/K log graph is the smoothed curve

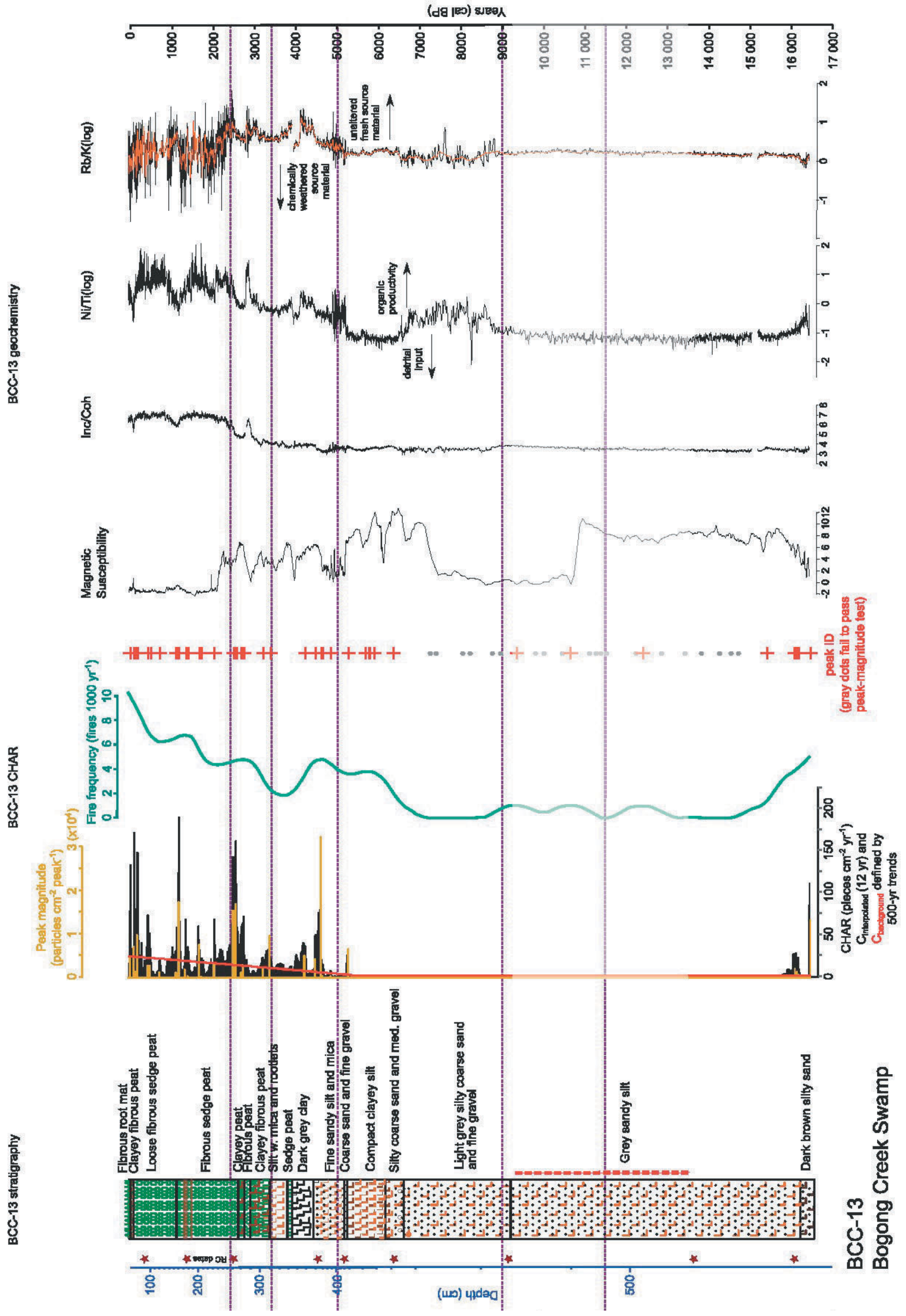

Figure 6. Summary of results from BCC-13. Fire history based on CharAnalysis (Higuera et al. 2009); vertical red dotted line and paled sections indicate poor chronological control; major chronological phases indicated. The orange line in the Rb/K log graph is the smoothed curve.

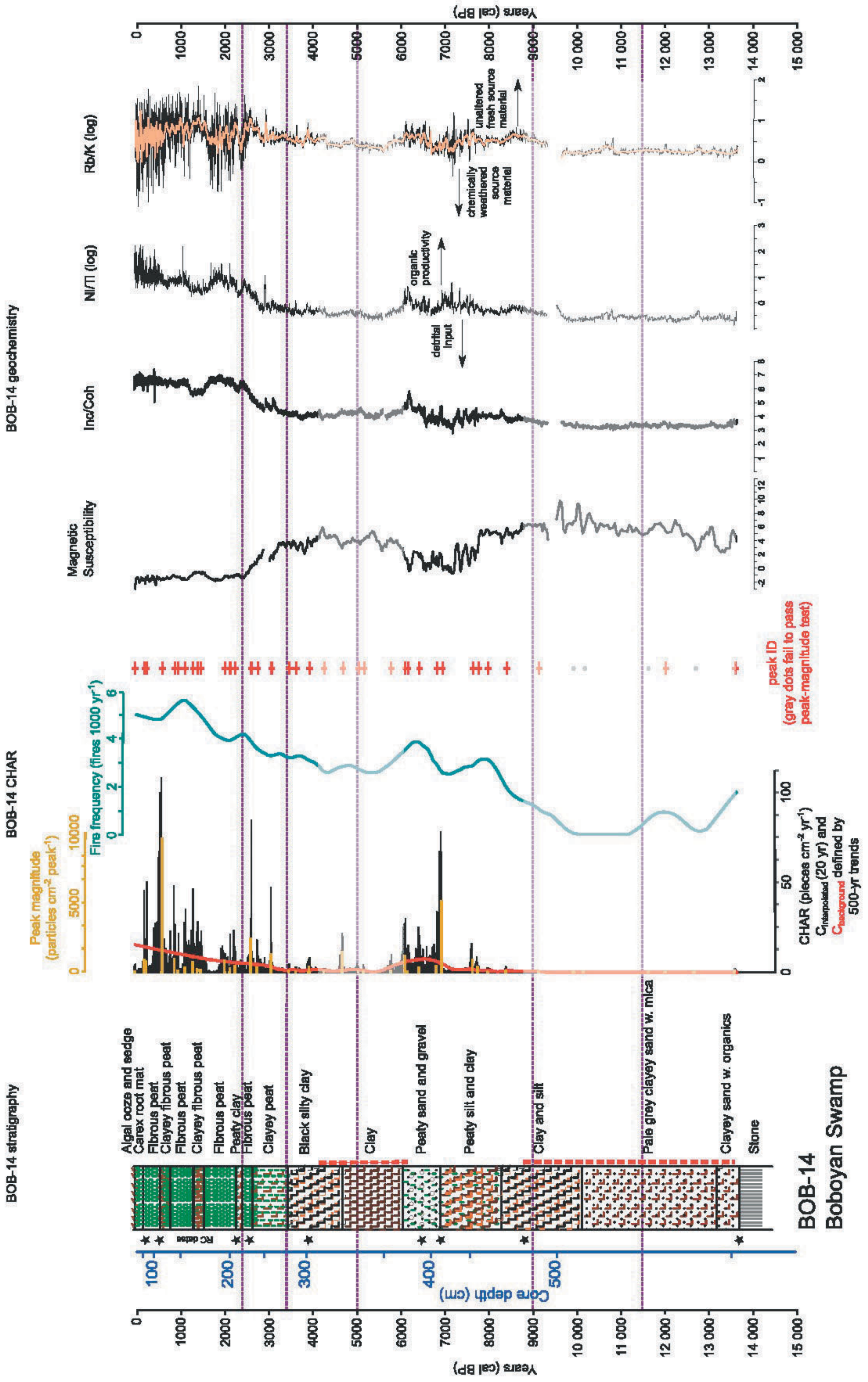

Figure 7. Summary of results from BOB-14. Fire history based on CharAnalysis (Higuera et al. 2009); vertical red dotted lines and paled sections indicate poor chronological control; major chronological phases indicated. The orange line in the Rb/K log graph is the smoothed curve.

consisting of clayey sands and clayey silts, potentially missed segments through erosion or decomposition. The basal sediments date to just after 14 ka and includes organics. The early-to-mid Holocene record, from ca 9 to ca 6 ka, consisted of thick layers of clay, silt, sand and gravel, but also included a distinct peaty component from around 8.5 to 6.05 ka corresponding with the *Pomaderris* phase of Martin (1986). Grey and black silty clays with occasional sedge leaves, lighter bands and mica flecks dominate between 6 and 3.4 ka but the chronology for this section, especially for its first two millennia, is less certain; based on the stratigraphic characteristics, there is the possibility that sediments may be missing or heavily decayed. Evidence of some organic loss in the top metre of the core is seen in a higher variability of the Ni/Ti ratio, which is the proxy for organic productivity, and its' disagreement with the organic content of the samples.

Geochemistry

Correlation coefficients and PCA analyses of element data identified elements that are probably of lithogenic/detrital origin – including Ca, Fe, K, Rb, Si, Sr, Ti and Zr – and elements that are dependent on organic and/or water content variability as measured by Inc/Coh scatter – in this case, and to varying extents, Br, Ni, S and Cl. Detrital elements displayed strong positive correlation with PCA axis 1 in all three cores. Nickel (Ni) displayed strong negative correlations with PCA axis 1 in NUS-15 and BOB-14. In BCC-13, Ni displayed a strong positive correlation with PCA axis 2 while Inc/Coh, a qualitative indicator of organic matter content, displayed a strong negative correlation with PCA axis 1. Bromine (Br), often used as a proxy for organic content (Fedotov et al. 2012; Kalugin et al. 2013), had a relatively weak positive correlation to Inc/Coh in all three studied swamps (from 0.251 in NUS-15 to 0.665 in BCC-13).

The highly significant correlation of Titanium (Ti) with other detrital elements – including Si (0.939 in NUS-15 to 0.806 in BCC-13), Fe (0.963 in BCC-13 to 0.869 in NUS-15), Ca (0.951 in BCC-13 to 0.746 in NUS-15) and K (0.863 in BOB-14 to 0.774 in BCC-13) indicated that its source was predominantly local.

DISCUSSION

Despite the close proximity and similar ecologies of the three fens, each core has varying well- and poorly-represented chronological sections. Segments identified as poorly chronologically controlled may reflect a scarcity or absence of original material, a slow accumulation over many millennia, a hiatus in growth/input, or the loss of original material from erosion, burning or oxidation due to hydrological change. Such 'gaps' are common in the peat, alluvial and fluvial deposits of southeast Australia, especially in the upper layers of sites that have been heavily impacted by European occupation. Each core, however, contains significant segments of well-represented sediment and peat accumulation, and the environmental history of the local area is stitched together from these. It would be expected that not all low intensity small fires will be recorded in the sediments, and the research by Constantine and Mooney (2022) showed that a limitation of cleaning samples with bleach is the loss of some charcoal. The possibility of biasing samples toward higher severity fires, while applying to all samples, may limit the ability of the study to differentiate the smallest and least intense fires and disguise the finer trends of some cool burn practices that would otherwise be visible or a prior undocumented record of indigenous activity.

A palaeoenvironmental synthesis of the Namadgi Ranges

Post LGM and terminal Pleistocene (16 to 11.5 ka)

The Namadgi peatlands owe their origins to the subsequent amelioration of climatic conditions following the LGM (Barrows et al. 2002), a hypothesis that accords well with Cadd et al. (2021), who found that a shift towards a warmer climate around 17.7 ± 2.2 ka is associated with increased biological productivity. While this is slightly younger than the 18ka date of the cessation of the LGM in inland southern Australia given by De Deckker et. al., (2020) from marine core data, the envelope does cover the earlier finding of a short glacial advance in the highest part of the Australian Alps around 16.8 ± 1.4 ka by Barrows et al. (2001) and the estimation of full deglaciation of by 16 ka by Turney et al. (2006). The earliest record represented in this study the Bogong Creek core (BCC-13), which goes back slightly before 16 ka, and represents conditions immediately following deglaciation. In general, peatlands in the region commenced accumulating sediments around 14 ka (Hope et al. 2009) or 15 ka (Kershaw and Strickland 1989), so the early record provided by BCC-13 is unusual.

The vegetation community present at that time would have been dominated by bog species on the low nutrient substrate of the basal sands and gravels, including *Sphagnum cristatum*, the Restiads *Empodisma minus* and *Baloskion australe* and the Epacrid *Richea continentis*, a community that is now associated with sub-alpine peatlands that are fed by groundwater emergence. A slightly lower Rb/K ratio, indicating wash-in of chemically weathered material, and varied but generally lower representation of detrital indicators (κ), and heightened organic productivity (Ni/Ti), combine to suggest the presence of wetland communities that experience influxes of catchment sediments.

As temperatures warmed and precipitation increased a greater organic sediment load would favour the establishment of fen plants including *Carex gaudichaudiania* and *Carex appressa* on the flatter sections of the drainage lines. These two species accelerate the transition of the peatland from bog into fen with the increased rates of organic sedimentation tending to smother the bog keystone species *S. cristatum*.

The Inc/Coh and Ni/Ti ratios are not well correlated in the lower BCC-13 core, and a higher Ni/Ti ratio without a corresponding rise in Inc/Coh may represent periods in which organic material accumulated but where the organic matter itself has since decayed/oxidised leaving only the dark clay matrix. As a redox insensitive diagenetically inert element commonly associated with silts and fine sand, Ti is used here as the denominator based on the assumption that it represents the background terrestrial detrital component of the sediment (Davies et al. 2015). Sediments significantly enriched in Ni may develop if reducing conditions develop rapidly (Tribovillard et al. 2006). Nickel is a good proxy for palaeo-productivity as it can be retained within the sediment even where organic matter may have been lost through bacterial activity after deposition, and indicate the original presence of organic matter after its decay in reducing sediment (Tribovillard et al. 2006).

From around 14 ka, Nursery Swamp (NUS-15) developed into a sedge fen. Despite relatively poor chronological control until the early Holocene, Boboyan Swamp (BOB-14) mirrors this: developing into a fully established sedge fen by the Pleistocene/Holocene transition. The fens have occupied the sites since.

The combined proxies from NUS-15 indicate a landscape dominated by terrigenous sediment input with a slowly increasing catchment organic productivity and sedge growth towards the Holocene. Frequent detrital influxes, combined with a low fire frequency of less than two fire events per millennium, indicates that catchment erosion events were not always linked to fire events. In a study of alluvial deposits on the lower Naas River, 35 km downstream from Boboyan Swamp, Erikkson et al. (2006) described a period of alluvial aggradation from 14 to 12 ka which they interpreted as reflecting a shift towards increased rainfall combined with incomplete vegetation cover, resulting in high erosivity causing hillslope instability and increased sediment yield. This hypothesis is generally supported by the NUS-15 data, where there is a reduction in the frequency of fire events coupled with the deposition of inorganic sediments.

At Nursery Swamp, phases of heightened landscape productivity are evident between 12.5 and 12 ka as indicated by trends in the Inc/Coh and Ni/Ti ratios toward increased organic matter and productivity. Combined with decreased detrital input and small fluctuations towards a lower Rb/K ratio, this may indicate a short period of relative landscape stability. Following that, one or more landscape events from 12 to 11.8 ka, seemingly unrelated to fire, appear to have resulted in some destabilisation of the Nursery Swamp catchment.

The Rb/K(log) ratio is used to identify enhanced chemical weathering of parent materials, and in turn represents a catchment erosion proxy. Both rubidium (Rb) and potassium (K) are significant components of the granodiorite that comprises the local Namadgi geology. Potassium is relatively water-soluble and thus more readily mobilised than Rb during chemical weathering reactions, especially in micas and feldspars (Muhs et al. 2001; Brown 2011). A reduced Rb/K ratio indicates a relative increase in the proportion of K, representing the presence of material that has been chemically weathered and accumulated in the landscape during stable periods. A high Rb/K ratio typically indicates deposition of less altered, or fresh source material, while a decrease in the Rb/K ratio indicates conditions suitable for limited mobilisation of chemically weathered material rich in K from the landscape, with the slower transport pathways equating to lower erosion rates in the catchment.

Early Holocene (11.5 to 9 ka)

The early Holocene was characterised by the rapid deposition of fibrous peat at Nursery Swamp from 11.3 ka, where increasing moisture and possibly warmth may have controlled this threshold. This mirrors the timing of establishment of organic fen sedimentation in nearby regions: on the western montane slopes of NSW by ca 12 ka (Kemp and Hope 2014); by 12.5 ka at 1400 m near Mt Kosciuszko (Hope et al. 2019); the transition from organic clays to peat at 12,000 ± 485 cal yr BP at Caledonia Fen in

Victoria (Kershaw et al. 2007 2010); and are slightly delayed in the alpine zone during the period 10-12ka Martin 1986 (a and b).

The early Holocene also sees the sudden appearance of significant charcoal accumulation at Nursery Swamp, and an increased fire frequency, averaging four events per millennium, and peaking at 6. Fire events at Nursery Swamp appear to cluster in groups during three main intervals in this period (11.5 to 10.9 ka, 10.3 to 9.8 ka, and just prior to 9 ka), stratigraphically situated near several clay bands in the core. Increased fire is also evident from 12 ka to just after 10 ka in the Kosciuszko Ranges to the south of the Namadgi region (Hope et al. 2019), matching a wider eastern Australian trend (Black et al. 2008). Heightened fire activity here reflects a greater biomass availability and more landscape scale fires, with no archaeological evidence of a broader generalised cultural change in the diverse range of subsistence strategies across the variable environmental gradients of the indigenous populations of eastern Australia at that time.

The early Holocene is also an organically productive time at Nursery Swamp, coupled with low detrital signals and a trend towards chemically weathered materials that suggest phases of slope stability. Phases of particularly high productivity occur from 10.8 to 10.5 ka and from 9.9 to 9.3 ka, both chronologically situated between a series of fire events which may indicate that productivity and the accumulation of organic sediments may have been stimulated by increased or more readily available nutrients in the landscape. Several erosion events occurred, notably one from around 9.6 ka that resulted in significant detrital influx and input of weathered inorganic material, that interspersed the second phase of high productivity.

A transition beginning shortly prior to 9 ka appears to have led towards a generally less stable landscape. It is possible that sediment deposits from the early Holocene at Boboyan and Bogong Creek are largely missing from these cores because of sediment loss due to instability that commenced from around 9.3 ka.

Early to mid Holocene (9 to 5 ka)

In the early-to-mid Holocene, productivity and organic growth, and sediment accumulation, may have been limited by landscape events that possibly included erosion or decay of older as well as contemporary swamp sediments. Each of the Namadgi cores contain segments from this phase, but the clay, sand and silt layers at Bogong Creek and Boboyan, and a very short undated peaty segment from Nursery, suggest that substantial records may be missing or truncated. Previous cores from Nursery Swamp (Hope 2006) also display preserved humic clays with bands of peaty silts from 10 to 3.5 ka, capped by sand lenses. Other peat forming sediments in the Namadgi area, such as the subalpine bogs at Ginini Flats and Rotten Swamp, appear to have lost any earlier Holocene fill, with peat accumulation recommencing only in the late Holocene (Hope 2009).

Sediment ‘gaps’ representing the early-to-mid Holocene, and generally corresponding to a Holocene ‘climatic optimum’ (HCO), are common in SE Australia. Mooney et al. (2021) found lower accumulation rates from 9.0 to 7.6 ka in the Sydney region, and attributed this to a more positive moisture balance, which allowed sufficient vegetation cover to increase catchment stability. Cohen and Nanson (2007) compared fluvial deposits across SE Australia and found that deposits dated from between ca 8.5 and 4 ka are relatively rare. They attributed this trend to increased rainfall and higher river flows, resulting in enhanced flushing of sediments and less sediment supply due to well-vegetated catchments having more opportunity for previous sediments to be eroded away, and less opportunity for fresh sediments to accumulate. Locally, for example, Erikkson et al. (2006) noted that no alluvial deposits dated between 12 and 3.3 ka remain preserved in the Naas valley downstream from Boboyan Swamp. Johnston and Brierley (2006) also speculated that the absence of alluvial fills between the late Pleistocene and 3.8 ka in Mulloon Creek to the east of the Namadgi Ranges may be due to the removal of early Holocene sediments prior to the commencement of peat formation. Despite some chronological uncertainty and possible gaps, the remnant early-to- mid Holocene sections from the Namadgi cores contribute substantially to the palaeoenvironmental history of the area. Chronological control for the Nursery core, NUS-15, is least certain.

At Bogong Creek, the early millennia from 9 ka to around 6.6 ka are quite distinct from the later part of this phase. The early period, represented by only a short core section, is characterised by seemingly few or insignificant detrital influx events, several cycles of heightened organic productivity clustering between 8.7 ka and 6.7 ka, and a prevalence of chemically weathered rather than fresh detrital material entering the system. The prevalence of Ni, despite very little change in the Inc/Coh ratio, suggests the accumulation – and subsequent decay or oxidisation – of organic material.

Boboyan Swamp, perhaps the most comprehensive of the three records for this phase, shows similar patterns, although the onset of the relatively productive cycles is subtle until around 8.3 ka and lasts longer, until around 6.1 ka. Thus, in the first two to three millennia of the Holocene, both the Bogong Creek and Boboyan Swamp cores indicate catchment conditions were dominated by organic rather than detrital cycles, which is similar to the Sydney region at that time (Mooney et al. 2021). The overall picture supports regional observations related to higher moisture availability of the HCO. These include increased wet heath and fen development from 8.5 ka (Hope et al. 2009); higher effective precipitation from ca 7 ka (Chappell 1991; Kershaw et al. 1991); and reduced aeolian activity in the Australian Alps from 7.6 to 5.5 ka (Stanley and DeDeckker 2002) and/or 6.5 to 5.5 ka (Marx et al. 2011).

It is around 6.6 ka and 6.1 ka, respectively, that the Bogong Creek and Boboyan records indicate marked changes. From this time both sites indicate more detrital input, and this trend continues into the mid to late Holocene at Boboyan Swamp.

The fire record for the period from 9 to 5 ka is also unusual and warrants further attention, particularly as the timing varies between Bogong Creek and Boboyan swamps. At Bogong Creek, the millennia *prior* to 6.6 ka are characterised by an absence of fire events. The stratigraphic and geochemical shifts towards detrital prevalence from 6.6 ka, noted above, are accompanied soon afterwards by the onset of a fire frequency averaging more than three events per millennium. Charcoal concentration is very low until just prior to 5 ka. There is a possibility that the last of these fire events, at around 5.2 ka, may correspond to a thin layer of coarse sand and gravel in the BCC-13 core.

At Boboyan Swamp, the millennia prior to 6 ka are characterised by a cluster of fire events occurring much earlier between 8.5 ka and 7.5 ka, and this is followed by another series of fire events between 7 ka and 5.7 ka, to average around three fire events per millennium during the combined early to mid Holocene phase. In contrast to BCC-13, the fire frequency in the mid Holocene at BOB-14 decreases following the stratigraphic and geochemical shift away from organic prevalence observed around 6.1 ka.

Some inconsistencies between sites are thus noted in relation to fire and other landscape proxies in the BCC-13 and BOB-14 cores for the time encompassing the HCO. Both cores are relatively well dated in these segments, so the chronological discrepancy is probably based on an actual difference in the timing of burning patterns between the two catchments. Higher charcoal accumulation rates from 8ka to 6 ka at Boboyan, compared with lower charcoal accumulation rates from 6.5 ka to 5.2 ka at Bogong Creek, may simply reflect higher precipitation rates or events coinciding with the times during which fires were burning in Boboyan valley rather than being a direct human fire signal.

Figure 8 shows fire frequency curves and events, with peaks identified, statistically inferred for all three fens. Intriguingly, when archaeological occupation dates from each catchment are plotted next to the fire records of that catchment, an interesting picture emerges. For both Bogong Creek and Boboyan, early to mid Holocene periods of increased fire frequency appear to overlap with phases of known human occupation in these valleys.

Mid to late Holocene (5 to 3.3 ka)

At ca 5 ka, the northern (tropical) and southern (temperate) climate systems are thought to have decoupled (Schulmeister 1999). In southern Australia, this would have led to increased westerlies, the loss of the summer monsoon rainfall, and a general sharp decline in effective precipitation. Locally, Kershaw et al. (1991) observed the replacement of *Casuarina*/Asteraceae with modern eucalypt-grassland associations at this time. Marx et al. (2009) attributed a dust pulse originating from the west from 5.5 to 4 ka, to a relaxation in southwesterlies. Marx and colleagues also found that the Lake Eyre Basin dust source to the west of the Australian Alps switched on after 4.8 ka; it is associated with arid and variable, ENSO-type, conditions. Stanley and DeDeckker (2002) also inferred progressively increasing intensity of aeolian activity from 5.5 ka from dust grain analysis in the Australian Alps. Instability of the local landscape is recorded as gravel bands in many alpine records, seen from 4.5 to 4 ka onwards by Kershaw and Strickland (1989) and interpreted as resulting from drier and cooler conditions.

At Bogong Creek, sediments are comprised of layers of clay and silt interspersed by sedge peat, and the phase is characterised by fluctuations in all proxies, a pattern that continues until around 2.5 ka. The Rb/K ratio is relatively high, indicative of a relatively high physical weathering rate, especially between 4.4 and 4 ka. These patterns, indicating a somewhat erratic start-stop trend to landscape dynamics, which match the expected, more varied, climatic conditions inferred from regional environmental observations. At Boboyan Swamp, the clayey nature of the core until ca 4 ka suggests that sections may be missing but in general, detrital signals dominate, and fluctuations in these allude to several detrital influxes. The NUS-15 record around 5 ka includes a short gap between core

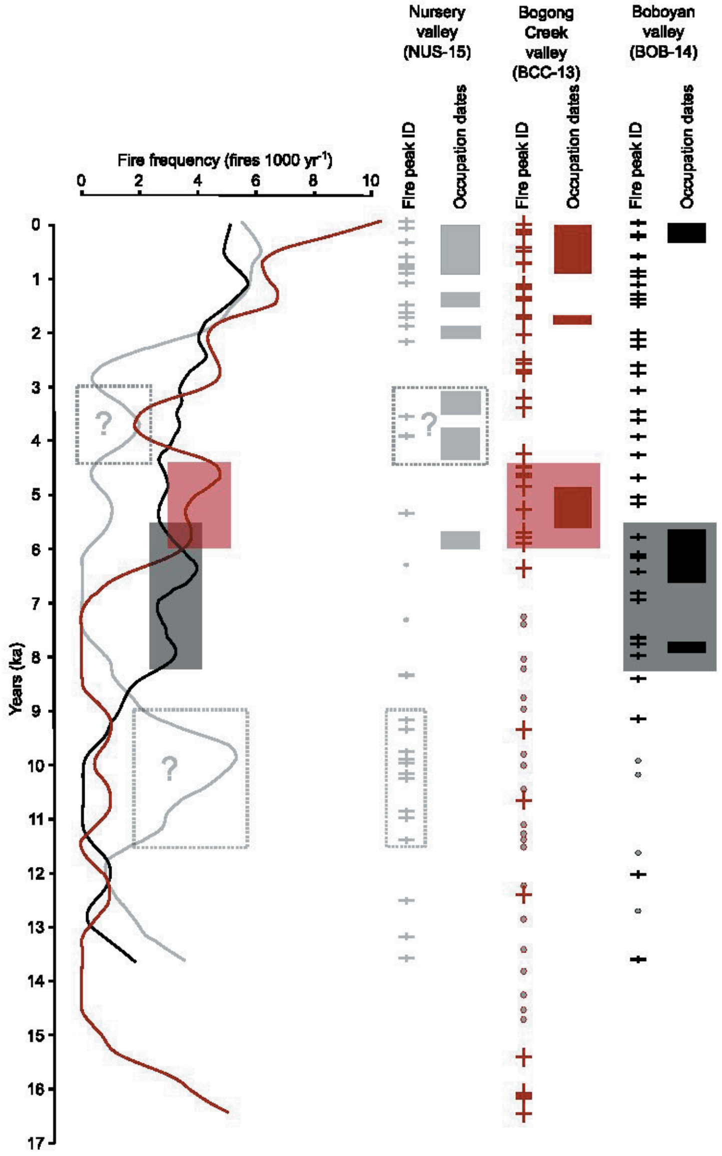

Figure 8. Fire frequency curves and events for Namadgi cores and corresponding occupation dates from archaeological sites within each catchment. Filled boxes indicate chronological overlap of human occupation and high fire frequencies during early to mid Holocene. Stippled boxes highlight other patterns referred to in text.

segments, but the records suggest the prevalence of productive conditions just prior to 4 ka, resulting in the accumulation of organic sediments.

The geochemical proxies and stratigraphic characteristics of all three Namadgi cores fit well into a regional picture of fluctuating climatic conditions from around 5 to 4 ka. Overall, however, there is no immediately noticeable transition from the preceding two millennia, also characterised by cycles of detrital influx. At Bogong Creek, although the overall charcoal accumulation increased after 5.2 ka. possibly suggesting larger more frequent fires, fire event frequency decreased after 4.5 ka. At Boboyan fire frequency varies around three fire events per millennium, and at Nursery, fire frequency between 5 to 4 ka remained low. Given that an ENSO-dominated climate would have allowed for the accumulation of biomass during the wetter phases and the drying and subsequent potential for burning of the biomass during drought periods, the low mid Holocene fire frequency is an interesting observation.

In terms of regional context, mid Holocene fire regimes in general do not show a consistent pattern. Increased burning from ca 5.5 ka is noted by Black and Mooney (2006) at Goochs Crater in the Blue Mountains, by Kemp and Hope (2014) on the western Southern Tablelands, and by Martin (1994) at Kurnell Fen near Sydney. Decreased fire regimes, however, are noted commencing around the same time at nearby Rotten Swamp (Hope and Clark 2008), in the Sydney basin (Mooney et al. 2007), and recently by Martin (2017) at Goochs Crater where Black and Mooney (2006) had previously described increased burning. Mooney et al. (2011) also note less overall burning in SE New South Wales after 5.5 ka. A human basis of this pattern can be considered, resulting from a geographically variable anthropogenic contribution to burning across parts of SE Australia.

Charcoal peaks dated to around 3.9 ka at BOB-14 and NUS-15, chronologically followed by terrigenous sediment fluxes in the NUS-15 and BCC-13 cores, possibly record a major regional fire event and subsequent catchment erosion. In the study of alluvial deposits of the upper Cotter catchment in the Namadgi area, Worthy (2012) observed a fire event associated with erosion dated to 3.8 ka. Combined, these fire records may well represent a single large-scale regional event around this time. Given the increased aridity noted in the literature for the preceding millennium, and the possible large scale of the fire, this event may signify an increase in frequency and severity of extreme fire conditions. Landscape recovery after the speculated regional fire-erosion event is also evident in the cores. The following centuries are characterised by a reduced fire frequency at Nursery and Bogong swamps. At Nursery Swamp in particular, detrital influx decreases as slopes stabilise with vegetation re-growth, and productivity in the catchment increases.

Early peat growth phase (3.4 to 2.4 ka)

The Namadgi cores date the onset of an initial rapid fibrous peat growth phase to between 3.4 ka and 3.2 ka., with a significant shift in many proxies. The change to rapid peat growth around this time is seen in most Namadgi swamps and coincides with other significant vegetation changes, notably low representation of eucalypt pollen in many records (Hope 2008; Kemp and Hope 2014). In Namadgi, the phase is accompanied by the onset of an increasing fire frequency that continues rising to the present.

Despite evidence for less terrigenous input from this time, aggradation of charcoal-rich alluvium dominates in the lower Naas Valley, downstream from Boboyan Swamp, from 3.3 ka (Erikkson et al. 2006). Cohen and Nanson (2007) also demonstrated that build-up of alluvial terraces began after 3.5 ka in SE Australia. Coupled with potentially drier conditions in the region after 3.5 ka (Stanley and DeDeckker 2002), alluvial aggradation beginning around this time could result from discrete events where fires were followed by rain events, rather than from a generally unstable landscape. Evidence of such events can be seen in the Namadgi cores up to the present.

Late peat growth phase (2.4 ka to present)

The late peat growth phase is separated from the early peat growth phase by an event or series of events occurring between 2.5 ka and 2.2 ka. Around this time, the Bogong Creek and Boboyan cores contain one or more dark clay bands with associated charcoal peaks, detrital influxes and signals of reduced productivity. The events occur at the possible start of a series of extreme and prolonged El Niño events affecting Australasia, as inferred from oxygen isotope signatures in coral in PNG (Gagan et al. 2004; McGregor and Gagan 2004).

The regional environmental record of this time provides evidence of cooler conditions with levels of higher effective moisture. Marx et al. (2009) proposing a wetter and more vegetated Murray River after 2.5 ka. An expansion of subalpine vegetation from 2.9 to 0.9 ka is attributed to neoglacial cooling (Kemp and Hope 2014), and a period of higher effective precipitation is recorded in western Victoria from 2 to 1.8 ka (Mooney 1997). From around 2.4 ka, the Namadgi swamps entered a rapid peat accumulation phase dominated by organic input, and accompanied by a high fire frequency that increased towards the recent past, averaging between five and six fire events per 1000 years during these millennia. There are numerous inferred fire events, yet only several appear to have affected the landscape significantly in terms of geochemical signals and stratigraphic visibility.

While there are no precise chronological correlations between the fens for individual events, a broad-scale fire event is tentatively dated to between 1.6 and 1.3 ka. It is inferred from a peak in detrital influx dated to 1.6 ka at Nursery, a series of dark charcoal-rich bands dated to between 1.4 and 1.3 ka at Bogong Creek, and a band of clay and detrital signal associated with a cluster of three fire events between 1.5 and 1.3 ka at Boboyan. Another episode of detrital influx following a charcoal peak is dated to 1.1 ka at Bogong Creek, intriguingly similarly dated to a fire event recorded by Worthy (2012) in the upper Cotter catchment. The event marks the transition to a less compacted fibrous sedge peat in Bogong Creek.

Interestingly, while three to four detrital influxes at Nursery Swamp between 0.8 to 0.4 ka may be linked to a series of fires during this time, possibly associated with a fire that affected the Boboyan catchment between 0.6 and 0.5 ka, there is no distinct evidence of such an event at Bogong Creek situated in between; in fact, there is very little evidence of fire events at Bogong Creek between 1.1 and 0.5 ka. The past 1000 years see the highest fire frequency in the histories of each of the cores. With records of fire frequency peaking around 1000 years ago at Boboyan Swamp, around 500 years ago at Nursery Swamp, and the during the post-European period at Bogong Creek Swamp. Bogong Creek records the landscape instability brought about by European impacts from the 1800s with heightened detrital and charcoal records in the upper layers.

There is some evidence of loss of organic matter in the top section of the BOB-14 record, with rapid variability and a rise in the Ni/Ti ratio without a corresponding rise in Inc/Coh curve. A trend seen to represent periods in which organic material accumulated but where the organic matter itself has since decayed/oxidised. As such, the limited signature of European occupation is more a taphonomic artefact than the effect of differing European land management strategies in the Namadgi Ranges. Draining, the regular burning of the swamp surface, and the introduction of hard hoofed animals impacted on the ability of the fens to faithfully record environmental change. Some indication of the comparative levels of oxidation and degradation of peats at the sites are seen in overall trends in the Ni content at each site, which showed good correlation to total organic carbon (Inc/Coh) for NUS-15 (0.905) and reasonably for BOB-14 (0.784), aside from the top of the core. There was a much low correlation for BCC-13 (0.131), indicating a significant amount of organic loss from the sediments.

It should be stressed that there was a dramatic shift in land management priorities between the pre-contact Aboriginal land management and the post occupation land management of the Namadgi ranges. The organic sediments prior to European occupation in the bottom sections of the cores were produced while there is archaeological evidence of a significant human population in the Namadgi Ranges, and illustrate that a healthy peatland was promoted while the peatlands were being used by this population for subsistence and other activities. This is very much in contrast to the effect of European land management on the health of the peatlands.

People, fire and the landscape

Various Australian studies have sought links between palaeoenvironmental fire records and targeted landscape burning by Aboriginal people. The recent debate around the nature of complex pre-European Aboriginal land management systems was ignited by Gammage (2012) and Pascoe (2014), and made the task of chronologically and geographically identifying and reconstructing complex human activities through deep time fall to the palaeoenvironmental disciplines. Many broad-scale (Bird et al. 2013; Mooney et al. 2011; Williams et al. 2015) and localised (Black et al. 2008; Mooney et al. 2007; Hughes and Sullivan 1981) comparisons of fire and archaeological datasets loosely discern a human contribution to burning amongst other factors such as climate and vegetation shifts. Fundamental to the issue of whether an anthropogenic element can be detected in the palaeoenvironmental records, are the questions of whether targeted fires lit by Aboriginal people produce charcoal signals that enter the palaeoenvironmental record, and how Aboriginal people used fire as a land management tool in the Namadgi Ranges.

Whitlock and Larson (2001) suggested that fire regimes characterised by frequent and efficient fires of low intensity and height do not produce a large amount of charcoal. Similarly, Prosser (1987) and Dodson et al. (1993) have argued that Aboriginal burning did not typically trigger increased erosion. Conversely, Hughes and Sullivan (1981) argued that valley fill increases during the last 3000 years were related to increased Aboriginal burning. While Clark (1983) determined that increased charcoal does not necessarily represent more frequent fires, she also found that most charcoal is transported by water, so charcoal in sediments provides a record of both fires and fire-rainfall events. It is also important to note that bushfires caused by natural events such as lightning strikes are also likely to have occurred occasionally throughout the region (Egloff 2017).

The small footprint of pre-European Aboriginal impact reflects the nature of their fire use, that is using small, low intensity burns heterogeneously in the landscape, and using fire within a climatic context, tailoring their use of fire to the prevailing climatic conditions. This interaction has been referred to a ‘climate-humans-fire nexus’ (Black and Mooney 2006). The landscape impact and the anticipated palaeoenvironmental signal for human induced burning is a combination of the climate and its effect on both ignition sources and fire behaviour, peatland morphology and taphonomy, human population and material culture, and the cultural and environmental context of fire.

Some studies have confidently associated fire regimes with the activities of people in Australia, including correlations with very low-level occupation or abandonment of Kangaroo Island (Clark and Lampert 1973) and Hunter Island (Hope 1978). More recently the context of these studies is framed both environmentally and culturally. In an examination of a peat record from western Tasmania, Fletcher et al. (2010) proposed that a marked increase in charcoal after ca 5.8 ka resulted from both the onset of ENSO variability and human occupation, significantly pre-dating the archaeological record of known occupation for this region. A decoupling of environmental variability from increased fire activity and climatic variability during a short phase in the late Holocene associated with a peak in human population growth, led Romano and Fletcher (2018) to interpret the anomaly as resulting from intentional management of a small area in north-west Tasmania during that phase.

It has been demonstrated that Aboriginal habitation in the Namadgi Ranges, in terms of when people were in the high country and how their technologies altered through the Holocene, may have differed substantially to that of surrounding lower altitude environments (Theden-Ringl 2016, 2017; Theden-Ringl and Langley 2018). Unlike less demanding environments surrounding the high country, the ranges were more frequently visited during periods of optimal environmental conditions, with activities being both short-term and seasonal. Two main phases of occupation, with differences in terms of stone tool assemblages, are evident in the Namadgi Ranges for the Holocene, while Pleistocene activity in the high country itself is yet to be found. An early phase is dated from *ca* 7.8 to just after 5 ka, and is represented by several, mostly sparse, occupation deposits at sheltered sites in the Namadgi valleys (Theden-Ringl 2016). The archaeological chronology matches a proposal by Williams et al. (2015) that the early to mid Holocene was a phase of increased exploration and occupation in response to opening of ecological and hydrological resources across the country. The palaeoenvironmental record of the Namadgi cores supports the scenario of a relatively productive landscape with well-established and moist vegetation.

Evidence of occupation in the Namadgi Ranges is reduced from ca 4.5 to 2 ka. The onset of this phase coincides with the start of a climatic pattern dominated by the El Niño – Southern Oscillation (ENSO), thought to have caused substantial stress to Aboriginal populations and resulting in technological and economic adaptations that are visible in the archaeological record of SE Australia (Hiscock 2008). Such adaptations are not known from the Namadgi Ranges for this time; and it appears the Namadgi Ranges became a more marginal environment for human habitation. Only one site in Nursery Valley, a significant rock art site, is known to have been visited by people during this time (Rosenfeld et al.1983).

The criteria for distinguishing human use of fire in the Namadgi palaeoenvironmental record includes archaeological evidence that fire regime changes coincide in space and time with changes in human history, and a demonstration that average frequency of fires differs from the potential fire frequency determined by climate and vegetation type derived from the palaeoecological record (Horton 1982; Bowman et al. 2011). These criteria are fulfilled several times in the terrestrial archives of the Namadgi Ranges. Firstly, the evidence of fire events correlates with the archaeological records in both space and time for the Bogong and Boboyan catchments, rather than being dependant on climatic changes. Secondly the fire frequency is comparatively depressed in all three records during drier and more erratic climatic conditions between 4.5 ka to 3 ka. Thirdly there is a small peak in the Nursery Valley fire frequency curve coupled with the contemporaneous archaeological presence in the valley, and a single pulse in the Rb/K curve around 4 ka, which hints at a weak but speculative link to the presence of people in the Nursery Valley utilising the area immediately around the peatland or even the peatland surface itself.

So, while a catchment specific human-fire connection could imply that other fire event increases, for example, in the Nursery catchment during the early Holocene between 11.5 ka and 9 ka, are evidence of as-yet an undocumented change in population or activities of people in the high country at that time, these must be interpreted in a climatic context.

Changes in abundance of different species in relation to climate change may drive increases in the human carrying capacity of the area during a specific season, where larger populations can be temporarily sustained in relation to specific resource availability. An example of this was the beginning of the current pattern of Bogong moth, *Agrotis infusa*, aestivation on the highest peaks in the alps following climatic amelioration sometime after the LGM (Keaney 2016). The indigenous occupation in the Namadgi Ranges has been continuous despite large climatic change in the area since the LGM, and illustrates a diversity of subsistence strategies were used through time, including variations in fire use and material culture.

Ethnographic information collected by Flood (1980) on the Aboriginal people's traditional use of fire in the past in the Namadgi Ranges, and in the Australian Alps more widely includes direct observational evidence that fire occurred in the tablelands and montane areas before settler occupation, although there is no direct observational evidence of firing in the higher sub-alpine and alpine regions. Dendrochronological records collated by Zylstra (2006) reveal that fire-free intervals in the Australian Alps were significantly longer prior to European burning practices, and that such fire-free intervals would have included the absence of both high intensity and low intensity fires. He concluded that Aboriginal management probably resulted in a far lower overall fire frequency in the Australian Alps than for the rest of SE Australia. Zylstra (2006) also emphasised several points based on interviews with Aboriginal land managers, noting the specialised control, understanding, discretion and planning of those responsible; and a spiritual view towards fire. Today Aboriginal land managers are increasingly involved in the active fire management of country, and are learning the management of fire through customary law. A more integrated fire and land management approach includes cultural burning opportunities for Aboriginal fire culture to restore landscape resilience to wildfires (Atkinson and Montiel-Molina 2023).

The nature of Aboriginal-instigated burning directly prior to European occupation in the Namadgi Ranges appears to be of low intensity, and targeted to specific purposes, including to clear and control scrub undergrowth to reduce the likelihood and impact of landscape scale fires, for travel routes, to attract game, to flush game, to encourage beneficial plant species and for cultural and spiritual reasons (Patton et al. 2023; Flood 1980; Kohen 1995; Zylstra 2006). The higher altitude Snow Gum woodlands were apparently seldom burnt (Banks 1982; Zystra 2006), with the use of fire more limited to lower altitude grasslands, grassy woodlands, dry montane forests and may even have included the fens themselves, but its' precise frequency is generally unknown.

This type of fire management can partially explain the apparent overall decrease in mid Holocene fire frequency between ca 5 ka and 3.5 ka in the palaeoecological record of the Namadgi Ranges, which is unexpected in a variable ENSO-dominated climate where biomass availability coupled with increased periods of drought may have increased the potential for landscape scale fires. The records do not clearly reflect a fire pattern controlled by solely by climate, instead a better explanation is that the fire record is an intersection between the climate, patterns of land use by the indigenous population and the impact of infrequent landscape scale fires.

Another unexpected trend in the palaeoecological records is that allochthonous inputs are limited in the Namadgi sites in the past 2000 years when after 3 ka there is an abrupt increase in the frequency and magnitude of ENSO widely suggested at this time (Clement et al. 2000; Sandweiss et al. 2001; Riedinger et al. 2002; Gagan et al. 2004), and there is an associated increase in the records of individual fire frequencies. Again, there is perhaps an Aboriginal element to the fire patterns observed in this period, reflecting an increase in low intensity fires, which may have included the deliberate and targeted low-impact burning of the valley-bottom grasslands for both subsistence and the reduction of the impact of increasing numbers of landscape scale fires, combined with the utilisation of the peatlands themselves.

As such, neither an anthropogenic contribution or climatic forcing can be dismissed altogether in explaining fire regime changes in the Namadgi Ranges. Indeed, there is a false dichotomy between the two. Indigenous occupation of the area has spanned periods of vast environmental change, which is recorded in the peatlands. Viewing the fire records from the point of view of a climate-fires-human nexus is a more wholistic and explanatory approach than isolating "natural" and "human" fire regimes.

Individuals in prehistory would use fire for resource manipulation in the context of environmental conditions. A poignant example being the utilisation of the peatlands themselves, which changed from *Sphagnum* bog in the basal sands and gravels and into *Carex* fen in the peat layers at the top of the profile. There would be different subsistence strategies used for bogs in the period of peatland formation in the late Pleistocene compared with the subsistence strategies that people used in a sedge fen during an ENSO dominated climate in the late Holocene.

CONCLUSION

This paper presents evidence from three long sediment cores to build an integrated palaeoenvironmental history of the Namadgi Ranges, beginning with the late Pleistocene swamp formation at about 16,000 years ago, to the present. The study demonstrates the importance of comparing multiple records within a region to identify and characterise both regional-scale forcing and discrete landscape events that affected one of the catchments. Inter-catchment contrasts and catchment-specific archaeological histories were also critical, allowing for the identification of some localised anthropogenic influences, and suggesting utilisation of the swamps themselves. As anthropogenic fire is very likely to have occurred in a very targeted approach, and at local spatial scales in a region of mostly sparse habitation, the research highlights the importance of matching scales in data analysis. This paper also sets the framework for further integration of landscape and archaeological knowledge in the Namadgi valleys in a more wholistic manner, by integrating the climate-human-fire nexus.

The landscape of the Namadgi ranges has undergone vast changes since the terminal Pleistocene, with periods of low productivity followed by periods of high productivity. Cycles of detrital influx, organic productivity and peat growth in the cores are contrasted with possible gaps in the sediment records, and attest to times of landscape stability, and also instability. Fire frequency was also found to be variable. By comparing environmental data from peatlands to local archaeological records a changing anthropogenic signature was uncovered, with the interaction of climate, humans and fire influencing each other.

Rather than trying to totally disentangle "natural" and "anthropogenic" fire events, this research has highlighted the environmental interaction between climate, humans and fire, factors which will affect a singular fire, the broader fire regimes and the even the long-term impact of extreme events where human occupation can have varied and multiple impacts.

Further studies which can give greater ecological contextual understanding, that can characterise individual landscape events and add chronological detail to peatlands, especially palynological analysis of the Namadgi fens, and rock-shelter deposits more generally will contribute to our understanding of archaeological and landscape interactions in the Namadgi Ranges and the high country.

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