Charcoal preservation and fire history in floodplain wetlands: problems and prospects

Buckiinguy Swamp in the southern Macquarie Marshes, 2017

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Declaration

I hereby declare this thesis has not been previously submitted to any other institution or university for a higher degree. This thesis is comprised entirely of my own work, except where acknowledged otherwise.

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Abstract

Fire plays an important role in floodplain wetlands, and wetland ecosystems respond dynamically in space and time to flooding, fire and geomorphological processes. Fire-climate-hydrology-vegetation interactions are complex and a multifaceted approach is required to understand and interpret fire history. This study investigated the use of macro-charcoal to interpret palaeo-fire regimes in the Macquarie Marshes. Sentinel Hotspot satellite data showed that Buckiinguy Swamp experienced 33 ignition points from 2002-2016, whereas Willancorah Swamp experienced 6 ignition points in this period. Macro-charcoal in contemporary sediment from Buckiinguy was used to estimate fluvial charcoal supply from upstream (13.5 ± 3.2 no. cm^{-3}). Despite taking account of fluvial inputs, macro-charcoal in sediment profiles from both wetlands was highly variable. Buckiinguy had macro-charcoal up to 90 no. cm^{-3} in the upper 40 cm (mean charcoal accumulation rate; CHAR 0.55 cm^{-2} a^{-1}), and Willancorah had up to 450 no. cm^{-3} in the upper 60 cm (CHAR 3.75 cm^{-2} a^{-1}). Sedimentology, geochemistry, and carbon stable isotopes ($\delta^{13}C$ range -15 to -25 ‰) were similar in both wetlands and quite uniform with depth. When combined with charcoal records, these proxies cannot be used with confidence to reconstruct local fire regimes. Water and wetland management could benefit from future palaeo-fire research if sufficient spatial and temporal assessment of fire and wetland conditions can be achieved.

Contents

Chapter 1 Thesis introduction

1.0 Environmental and fire history research in Australia

Past environments (palaeoenvironments) can provide valuable insights into change and variability within the environment, particularly where natural archives comprised of organic or inorganic material have built up over time. Naturally occurring materials that can be used as palaeoenvironmental proxies to help reconstruct environmental history (e.g. long-term fire dynamics) include pollen grains, charcoal, or fossils within sedimentary structures in terrestrial or aquatic settings (Kiage and Liu 2006; Conedera et al. 2009). Some of these environments accumulate and preserve material in the sedimentary record better than others, for example, wetlands including lakes and swamps (Long et al. 1998; Black et al. 2008). Palaeoenvironmental research can help assist in determining the resilience of ecosystems to environmental stressors, disentangle the natural or anthropogenic environmental changes over time, and assess present and future trajectories of environmental change for management purposes (Anderson et al. 2006; McWethy et al. 2013; Minckley and Long 2016).

Fire plays a pivotal role as a disturbance agent in many landscapes around the world and is often linked with environmental change, thus, the coupling of palaeofire and palaeoenvironmental research can be used together to aid the process of reconstructing fire history (Petherick et al. 2013). The Australian landscape is prone to fire and over time fire regimes have changed the structure, composition and distribution of both biological and vegetation communities (Bradstock 2010; Mooney et al. 2011). Periods of increased fire activity may represent periods with higher fuel loads (i.e. greater biomass), or greater ignition potential, or more intense burning (Black et al. 2007). Fire alters land cover, air and water quality, and other biogeochemical factors that have feedbacks to climate, hydrology and vegetation (Mooney et al. 2011). Knowledge of past fire regimes can provide insights into past environmental conditions, such as periods of variability and change in climate, hydrology and ecology (Mariani et al. 2016). Understanding the links between fire regimes and environmental conditions is paramount not only to humans but the environment, where global projections suggest the intensity and frequency of fire will increase under warmer and drier climate (Moritz et al. 2012). However, fire severity and intensity are difficult to understand as their relationship between vegetation-climate-people are inherently complex and non-linear (Power et al. 2008).

1.1 Fire in floodplain wetlands

Wetlands can be regularly or irregularly inundated ecosystems, with inputs of fresh or saline water supporting a variety of terrestrial and aquatic flora and fauna (Tooth and McCarthy 2007). The impact of fire in floodplain wetlands can varying depending on the severity and intensity of the fire, and can vary from: mortality of currently existing flora and fauna, loss of food and habitat, poor water quality, and loss of life and infrastructure (Bond and Keeley 2005). Inland floodplain wetlands respond dynamically to flooding, drought, fire and geomorphological processes but these have been poorly documented and poorly understood features (Tooth and McCarthy 2007; Ralph and Hesse 2010). Wetland environments provide a number of key ecosystem services which contribute to and improve society globally, these include: flood mitigation, water quality improvement, food production and water storage (Tockner and Stanford 2002). For example, inland rivers in Australia are driven by highly variable weather and climatic patterns, which influences the frequency, magnitude and duration of inland flooding events in response to localised catchment rainfall and runoff (Rogers and Ralph 2011). Knowledge of palaeofire regimes can help provide insights into previous environmental conditions, particularly to shed light on the stressors and resilience of floodplain wetlands which can help in differentiating between natural and human-induced environmental change in wetlands.

1.2 The Macquarie Marshes

The Macquarie Marshes are a large, multichannelled floodplain wetland system located on the lower reaches of the Macquarie River in central west New South Wales, Australia. As a Ramsar-listed wetland it is recognised for its ecological significance due to the habitat it provides for floodplain wetland biota with specific water requirements (Rogers and Ralph 2011), including refuge and habitat for colonial and migratory waterbird species (Kingsford and Auld 2005; OEH 2013). The wetlands begin to form when the Macquarie River begins to break down into numerous anastomosing and distributary channels forming the southern Macquarie Marshes, with semi-permanent and ephemeral aquatic vegetation (Yonge and Hesse 2009; Ralph and Hesse 2010). The southern Macquarie Marshes vegetation consists of river red gum (*Eucalyptus camaldulensis*) trees occupying the riparian zone of river channels, together with riverine woodland forests of coolabah (*Eucalyptus coolabah*) in the northern Marshes (Ralph et al. 2016). Common reed (*Phragmites australis.)* and bulrush stands (*Typha spp.*) occur in and adjacent to the channels and swamps within the wetlands that receive regular inundation (OEH 2012; Ralph et al. 2016). The wetlands of the northern and southern Macquarie Marshes Nature Reserve (Figure 1) were listed under the Ramsar

Convention for their international significance in 1986, and cover ~10% (~219 km^2) of the total (2000 km^2) wetland area (OEH 2013).

The Macquarie Marshes have had a long history of human occupation and utilisation prior to and after European settlement, which presumably also includes the use of fire for millennia. Archaeological evidence of Aboriginal activity over thousands of years is present in the form of earth mounds along the Old Macquarie River (Balme and Beck 1996). Since exploration and settlement by Europeans between 1818 and 1830, cattle and sheep grazing and other farming practices have spread in the wetlands and on the surrounding floodplains (Ralph et al. 2016). Fire has been used historically to burn the reed beds, usually coincident with seasonal flooding in late winter-spring, where it was used as a tool to promote vegetation regrowth for cattle grazing. However, this practiced ceased in circa 1990 as grazing licenses expired in the Nature Reserves (OEH 2012). In addition, flow diversion in the post-European settlement period has had a significant impact on hydrology within the system, particularly since the installation of Burrendong Dam in 1967 (Kingsford 2000).

Official records of fire activity and extent did not commence in the core wetlands until the Macquarie Marshes were designated as a reserve in 1971, before which only anecdotal evidence of fire existed (NPWS 1999; OEH 2012). Since 1947, however,18 wildfires are known to have occurred within or adjacent to the reserves, with four major fires (in 1947, 1966, 1994, and 1995) occurring in the northern section of the marshes and burning an area of more than 10 km^2 (NPWS 1999; OEH 2012). These major fires in grasslands, reed beds and riverine forests occurred during drought periods when seasonal flooding did not occur in the severe storm season from November to March (NPWS 1999). In the Nature Reserve, the main cause of fire ignition has been lightning strikes which has resulted in 90 % of fires during storm season (OEH 2012). Despite the occurrence and severity of recent fires in the Macquarie Marshes, to date, there have been no studies or documentation of the long-term fire history, or of the interactions between fire and ecosystem processes in the wetlands (OEH 2012). Limited contemporary data and a lack of palaeofire records mean that a major knowledge gap remains regarding the spatial and temporal patterns and impacts of fire in the Macquarie Marshes.

1.3 Research question and aims

The overarching research question of this study is *"Can macro-charcoal combined with other environmental proxies be a reliable indicator of past fire activity in the Macquarie Marshes?"*

The specific aims of this study are to:

1. Determine whether there an interpretable fire history in the sediment profiles of Buckiinguy and Willancorah Swamps based on analysis of macro-charcoal in sediment.
2. Measure the type and amount of fluvial charcoal entering the system from upstream to distinguish a background of macro-charcoal supply from *in situ* macro-charcoal in sediment cores linked to wetland fire history.
3. Examine whether macro-charcoal, combined with other environmental proxies, can provide evidence of a fire regime in the wetlands, which may then help guide future fire management.

1.4 Thesis structure

This chapter introduced the importance of palaeofire and palaeoenvironmental research in wetlands, provided an overview of the knowledge gap that exists for floodplain wetland environments, and presented the research question and aims of the study. Chapter 2 is a brief review of relevant literature addressing some of the merits and challenges associated with palaeofire and palaeoenvironmental research in Australia and abroad, with a focus on applications to wetlands in south-eastern Australia. Chapter 3 is a full draft manuscript targeted for the journal *Earth Surface Processes and Landforms*. The paper describes the methods and results from the study in detail, and discusses the findings from the Macquarie Marshes in the context of other studies. Chapter 4 summarizes the major research findings and their relevance to the aims of the thesis.

Chapter 2 Review of fire history and environmental research in wetlands

2.0 Introduction

This chapter reviews and synthesizes the current literature of fire history and environmental research in wetlands. In particular, the review focusses on the merits and challenges of attempting to reconstruct the palaeofire history and environmental conditions using a multiple proxy approach in wetlands of semi-arid and temperate Australia.

2.1 Importance of palaeoenvironmental and palaeofire research

Palaeoenvironmental reconstructions can provide a wealth of information about ecosystems and landscape condition over time while also being a highly useful tool for landscape management and conservation practices. Environmental knowledge extracted from these long-term records that extend beyond contemporary records can help to identify past natural changes, establish pre-impact states, and model possible future pathways (Dearing and Jones 2003; Beaty and Taylor 2009). The interpretation of palaeoenvironmental records essentially involves separating environmental change (i.e. natural processes) from the anthropogenic factors (e.g. post industrial revolution) that have affected or enhanced environmental change (Wilkins et al. 2013). Contemporary environmental events and regimes can be placed into longer-term contexts through the utilisation of palaeoenvironmental and palaeofire records. These records can reveal past changes in climate and weather patterns, which can be applied to regions that are strongly influenced and characterised by climatic variability (e.g. Australia) (Gouramanis et al. 2013; Petherick et al. 2013; Reeves et al. 2013). Additionally, the combination of palaeofire and palaeoenvironmental research can help identify the importance of fire in the landscape and associated feedbacks that inherently occur between fire, climate and other environmental conditions (Mooney et al. 2011; Stahle et al. 2016).

2.2 Previous significant research in wetlands

A majority of wetlands are either seasonally or permanently inundated ecosystems, with inputs of fresh or saline water supporting a variety of terrestrial and aquatic flora and fauna communities (Tooth and McCarthy 2007). Wetlands are most commonly located in humid and temperate zones around the world that are characterised by reliable and frequent rainfall, however many wetlands also occur in semi-arid or arid regions (i.e. drylands) (Tooth and McCarthy 2007; Tooth et al. 2014). These different wetland environments provide a variety of ecosystem services which contribute and improve human society globally. Some examples include: flood mitigation, water quality improvement, food production and water storage (Tockner and Stanford 2002).

Despite these benefits, floodplain wetlands, not only in Australia but also globally, remain poorly understood and documented environments (Tooth and McCarthy 2007; Ralph and Hesse 2010).

Australia is a fire prone continent and fire will continue to play a major role in the future, however, Australia and other regions in the Southern Hemisphere have lacked comprehensive long-term and continuous palaeofire or palaeoenvironmental records in contrast to many regions in the Northern Hemisphere (Black et al. 2006; Mooney et al. 2011). Palaeoenvironmental and palaeofire research is fundamentally based on robustly dated, multi-proxy evidence and high-resolution records. This allows for the dissemination of information of past environmental change separating the natural and human-induced change in the landscape (Gouramanis et al. 2013; Wilkins et al. 2013).

In Australia, both palaeoenvironmental and palaeofire research has mostly been confined towards the east-coast humid margins of Australia, New South Wales and Tasmania (Black and Mooney 2006; Mooney and Tinner 2011). These regions across the eastern portion of the country provide highly suitable conditions for the preservation of organic material (e.g. pollen, charcoal, macrofossils) that have been subjected to either permanent or semi-permanent wet conditions in the past (see Table 1). On the other hand, there is a paucity of palaeoenvironmental and specifically palaeofire research across drier climatic regions of the continent, because these drier landscapes do not preserve organic material such as charcoal well overtime (Bateman et al. 2007; Mooney et al. 2011). The Australian drylands are home to some unique, high-valued and variable ecosystems, including permanent, intermittent or ephemeral lakes and wetlands which have attracted the status of either national or international importance (Kingsford et al. 2004; Rogers and Ralph 2011). Despite this, a large gap remains in the body of knowledge for wetland and lake environments from these arid and semi-arid regions of inland regions, and their resilience to fire and hydrological change due to shifts in climate.

In particular, palaeoenvironmental studies are scarce across semi-arid regions of inland NSW, where only a few studies have been conducted to date, including: the Macquarie Marshes (Yu et al. 2015), Cuddie Springs (Field et al. 2002) and Ulungra Springs (Dodson and Wright 1989) (see Table 1). Yu et al. (2015) provide a high-resolution (decadal-centennial scale), multi-proxy palaeoenvironmental record of the northern Macquarie Marshes, extending the record from the Late Holocene to Late Pleistocene. Field et al. (2002) provided a record of changing environmental conditions of Cuddie Springs (an ephemeral lake), spanning back to the Late Pleistocene. However, the Cuddie Springs record is incomplete between ~19-6 ka due to archaeological disturbance leaving no intact Holocene record. Dodson and Wright (1989) provide a vegetation record for the

last ~30 ka at Ulungra Springs in central NSW. Like Cuddie Springs, the environmental reconstruction from Ulungra Springs is incomplete, partly due to the degraded and insufficient record throughout the upper ~1 m of the profile. These sites are situated in low elevation settings characterised by floodplain wetlands or freshwater lakes that are either ephemeral or intermittently inundated (Kingsford et al. 2004). Woodward et al. (2014) also mention there are no palaeoenvironmental records in high elevation arid, semi-arid, and temperate inland locations in NSW, in particular where these regions would be more sensitive to temperature and rainfall changes.

Table 1: A selection of palaeoenvironmental and palaeofire research from Australia and internationally from terrestrial lake and wetland environments (adapted from Petherick et al. 2013).

Climate zone and location	Site location	Study site	Elevation (m.a.s.l.)	Proxies	Record length (ka BP)	Reference
Temperate South Australia	34°58'S 138° 41'E	Wilson Bog	710	Charcoal, OSL, radiocarbon.	~7.0	(Buckman et al. 2009)
Temperate Tasmania	43°12'S 146°45'E	Lake Osborne	924	Charcoal, pollen, magnetic susceptibility geochemistry.	6.5	(Fletcher et al. 2014)
Temperate Tasmania	41°38'S 145°57'E	Wombat Pool	998	Charcoal, pollen, magnetic susceptibility, radiocarbon.	17	(Stahle et al. 2016)
Temperate New South Wales	32°30'S 152°19'E	Worimi Swamp	8	Charcoal, fire-scars.	2.8	(Mooney and Maltby 2006)
Temperate New South Wales	30°05'S 151°46'E	Little Llangothlin Lagoon	1350	Charcoal, macrofossils, radiocarbon, LOI.	20	(Woodward et al. 2014)
Temperate New South Wales	33°27'S 150°16'E	Goochs Swamp & Goochs Crater Right	~960	Charcoal, LOI.	14.2	(Black and Mooney 2006; Black et al. 2008)
Temperate New South Wales	33°18'S 149°0'E	Dunphy Lake	~700	Charcoal, XRF, OSL, pollen, radiocarbon,	~2.2	(Lobb 2015)
Semi-arid New South Wales	30°37S 147°31'E	Cuddie Springs	127	Charcoal and Pollen.	~30	(Field et al. 2002)
Semi-arid New South Wales	31°43'S 149°6'E	Ulungra Springs	380	Charcoal and pollen.	30	(Dodson and Wright 1989)
Tropical Queensland.	17°22'S 145°32'E	Bromfield Swamp	754	Charcoal, XRF, magnetic susceptibility, $\delta^{13}C$.	37	(Burrows et al. 2014; Burrows et al. 2016)
Tropical Queensland	17°37'S 145°70'E	Lynch's Crater	~760	Charcoal, geochemistry, pollen, LOI.	230	(Kershaw et al. 2007)
Tropical Queensland	17°10'S 146°38'E	Lake Euramoo	718	Charcoal, diatoms, pollen, magnetic susceptibility, LOI.	23	(Haberle 2005; Tibby and Haberle 2007)

Table 1: continued.

Climate zone and location	Site location	Study site	Elevation (m.a.s.l.)	Proxies	Record length (ka BP.)	Reference
Temperate Oregon Coastal Range, USA.	44°10'N 123°35'W	Little Lake	210	Charcoal, pollen, magnetic susceptibility, radiocarbon.	9.0	(Long et al. 1998)
Semi-arid Yellowstone National Park, USA.	44°25'N 110°35'W.	West Thumb, Duck, Mallard, Dryad and Grizzly Lake	~2400	Charcoal, dendrochronology, magnetic susceptibility, Lead-210.	0.75	(Millspaugh and Whitlock 1995; Higuera et al. 2011)
Semi-arid Sierra Nevada, California, USA.	37°35'N 119°00'W	Barret & Gaylor Lake	~3000	Charcoal, magnetic susceptibility.	9.2	(Hallett and Anderson 2010)
Temperate South-eastern British Columbia, USA.	49°20'N 116°54'W	NEL03	2074	Charcoal, pollen, magnetic susceptibility, pollen.	9.0	(Courtney Mustaphi and Pisaric 2014)
Alberta, Canada	52°53'N 118°3'W	Little Trefoil Lake	1026	Charcoal, pollen, dendrochronology.	3.5	(Davis et al. 2016)

South-eastern Australia is highly susceptible to wildfires and plays an important role as an ecological disturbance agent within the landscape. Fire threatens human life, properties, infrastructure and causes widespread environmental damage, and will play a major role in the future especially under an already changing climate (Lucas et al. 2007; Bradstock et al. 2014). However, there is a lack of palaeoenvironmental research that explores the long-term effects of environmental change, climate and anthropogenic activities that enhances our understanding of palaeofire history within NSW. There are only a few palaeofire history reconstructions studies conducted in temperate and semi-arid regions in south-eastern NSW that have a continuous long-term fire history record (Table 1). Internationally, there have been multiple studies reported in the United States and Canada (Table 1), which have produced short and long-term fire records using charcoal and other environmental proxies from sedimentary lake environments. The spatial and temporal coverage of these sites across the eastern Australia is uneven and fragmented. Therefore, there is a need for more attention in inland arid and semi-arid regions which can help reduce the spatial and temporal knowledge gap of understanding and interpreting fire history.

2.3 Establishing palaeofire records in wetlands

Lakes, a subset of wetlands, are sedimentary basins that often provide unique and invaluable environmental archives given that they tend to accumulate matter continuously over time (Whitlock

and Larsen 2001; Power et al. 2010). Other types of wetlands may also collect sediment, but perhaps not as continuously or without post-depositional modification. Wetlands, and particularly lakes, can integrate environmental (Meyers 2003), fire (Black and Mooney 2006; Stahle et al. 2016), climatic (Saunders et al. 2012) and anthropogenic changes (Tylmann 2005) into high-resolution sedimentary archives. These records contain information on past changes at both local and regional scales within and outside the catchment area (Whitlock and Larsen 2001; Birks and Birks 2006). Lake environments generally have high preservation potential of organic and inorganic material, site stability and consistent input of sediment over time (Conedera et al. 2009; Power et al. 2010). This requires sampling at fine resolution (i.e. continuous sampling) of lake sediment cores, while taking into account two major assumptions (1) minimal disturbance of sediments, vertically or horizontally (e.g. bioturbation or physical transport), and (2) chronological control is sufficient (annual laminations) throughout the core (Larsen and MacDonald 1993). If these assumptions hold, these annually laminated cores can provide observations (e.g. vegetation history, climate change, sediment transport etc.) at seasonal to decadal timescales, extending the long-term record and documenting these processes overtime (O'Sullivan 1983; Larsen and MacDonald 1993).

Sediment cores extracted from these sites can be subjected to various types of analysis (physical, chemical or biological) which can be used to help reconstruct past environmental changes for the question at hand. For example, some of the physical, chemical and mineralogical properties of sediment include: particle size, loss on ignition, magnetic susceptibility and ITRAX (Black et al. 2008; Fletcher et al. 2014). Equally important, the preservation of biological remains such as: charcoal (Whitlock and Millspaugh 1996; Long et al. 1998; Black et al. 2006), stable isotope analysis (Staddon 2004; Burrows et al. 2016), pollen (Kershaw et al. 2007; Stevenson et al. 2015), and macro and microscopic plant remains (Woodward et al. 2014; Kobayashi et al. 2015).

Typically, palaeoenvironmental research focusses on small, ‘closed’ systems such as small lake basins, crater lakes or hydrologically isolated depressions. Small sized catchments with small closed-in lakes in high-elevation areas are more sensitive to local changes, where minor fluctuations or adjustments in lake levels are driven by environmental and climatic changes (Larsen and MacDonald 1993; Woodward et al. 2014). However, despite the attractiveness of choosing environments with relatively stable and small catchment area sizes, there has been limited interest pursing fire history records in large catchment areas (see Table 1). Possibly due to the complex interactions within large fluvially dynamic catchments where catchment morphology, stream input or output, and source of local vegetation can affect deriving the source of particulate charcoal (Power et al. 2010).

Large lake basins or rivers and wetlands in large catchments ('open' systems) can record major events over long-time scales, making them valuable recorders of information, however, these settings have their own limitations when used in palaeoenvironmental research (Willams et al. 1998). Lakes situated within large catchment areas are more likely to buffer small and brief environmental or climatic changes, and generate a greater lag between the initial change and lake recording the impact (e.g. sediment delivery, water level changes) (Willams et al. 1998). The greater range of external factors influencing sediment delivery, vegetation growth, hydrology, and geochemistry in 'open' systems increases the complexity of a sedimentary record. This complexity must be acknowledged when drawing conclusions about apparent drivers of changes in a sedimentary record in an open, or more hydrologically or geomorphologically complex, system.

2.4 Methods applied towards palaeoenvironmental and palaeofire research

Palaeoenvironmental research incorporates multiple disciplines and sub-disciplines in the sciences which are governed by the research question being addressed. It is comprised of field-based research, using robust sampling strategies and the most applicable laboratory and computing techniques.

2.4.1 Charcoal analysis

The formation of particulate charcoal is due to incomplete combustion of organic material (Power et al. 2010). Since the work of Iversen (1941) charcoal identification from sediment cores has become an attractive and widely used method in an attempt to reconstruct previous fire regimes (e.g. Clark 1988a; Clark 1988b; Millspaugh and Whitlock 1995; Long et al. 1998; Gavin et al. 2006). Particulate charcoal is extremely useful as an indicator of fire episodes within a sedimentary record, that goes well-beyond the temporal limitations of fire scar chronologies (Clark 1988b; Whitlock et al. 2008). Charcoal records when combined with other environmental proxies, can become powerful records to aid the interpretation of climate-fire-vegetation linkages (Patterson et al. 1987; Fletcher et al. 2015). Charcoal may originate from either a local source (inside the catchment) or a regional source (outside the catchment) depending on the dispersal, transportation, and depositional conditions of particulate charcoal (i.e. charcoal taphonomy) (Conedera et al. 2009). Patterson et al. (1987) and Clark et al. (1998) have both suggested that the size of charcoal particles could be used to indicate the distance of the charcoal has travelled from the source area, where larger particles (>125 µm; macro-charcoal) would represent a local source and, conversely, smaller particles (<125 µm; micro-charcoal) would indicate a regional source.

Essentially, this approach is based on post-fire charcoal being rapidly deposited shortly after a fire event (i.e. peak component) and secondary charcoal that is introduced during non-fire years

(i.e. background component) (Whitlock and Larsen 2001; Conedera et al. 2009). For example, studies that have used macro-charcoal have reconstructed fire histories when combined with either radiocarbon (^{14}C) dating or luminescence dating techniques to first establish age constraints (i.e. chronological control) on collected sediment cores. Black and Mooney (2006) reconstructed Holocene fire history using macro-charcoal combined with ^{14}C dating from Gooch's Crater Right in the Blue Mountains, eastern Australia. Additionally, Woodward et al. (2014) presented a Holocene record investigating environmental change between wet and dry phases, where they used ^{14}C dating and macro-charcoal combined with plant macrofossils. Buckman et al. (2009) used luminescence dating combined with ^{14}C and climatic records to disentangle the Holocene fire history in Wilsons Bog in South Australia.

2.4.2 Sedimentology

Over time lake environments naturally accumulate organic and inorganic material which eventually lead to the formation of stratigraphic columns, thus providing researchers with a valuable source of data to reconstruct palaeoenvironmental and palaeofire history (Kiage and Liu 2006; Conedera et al. 2009). The degree of sorting, rounding, and the size of sediment particles can reveal what type of conditions prevailed during the period of sediment deposition (e.g. high energy fluvial activity, or low energy slackwater) (Håkanson and Jansson 2002; Hatfield et al. 2010). While there are important palaeoenvironmental changes that can be highlighted by sedimentological analysis, it is generally paired with other geochemical or geochronological techniques.

2.4.3 Geochemistry

Elemental variations down split sediment cores can be determined by geochemical analysis, which can help infer environmental changes, pollution inputs and assist in correlation studies (Croudace et al. 2006). X-ray fluorescence (XRF) spectrometry is a well-established analytical technique used to estimate the elemental composition of sediment and rocks (De Vries and Vrebos 2002; Croudace et al. 2006). ITRAX is a micro-XRF core scanning system that records a radiographic and optical image of a sediment core and identifies elemental composition at very high resolution (e.g. 200 µm) and is non-destructive (Croudace et al. 2006). Elemental composition or ratios can be used to infer different environmental processes (e.g. erosion, increased runoff/rainfall, transport of fine materials and detrital input) within catchments source areas (Davies et al. 2015).

2.4.4 Stable Isotope analysis

Stable isotope analysis of carbon (i.e. $\delta^{13}C$) can be a useful tool in palaeoenvironmental research, because it can help disentangle historical shifts between C3 and C4 ecosystems over

varying timescales, which is relevant to climate change and land-use issues (Ehleringer et al. 2000; Staddon 2004). The two most common isotopes of carbon in the environment are ^{12}C (98.9 %) and ^{13}C (1.1 %) (O'Leary 1988). There are two main values that discriminate the $\delta^{13}C$ signature of C3 and C4 plants due to differences in ^{13}C:^{12}C isotopic ratio, where: (1) C3 plants are typically woody species with values range between -40 to -20 ‰ and, (2) C4 plants consist of grasses with values -17 and -9 ‰) (Farquhar et al. 1989; Leng and Marshall 2004; Staddon 2004). C3 plants cannot limit photorespiration due to stomatal constraints and environmental stress (e.g. water and temperature), whereas, C4 plants have an adaptation allowing them to limit photorespiration (e.g. stomatal closure) under pressure from environmental stressors (O'Leary 1988; Farquhar et al. 1989; Ehleringer et al. 2000). Stable isotope analysis could complement fire history as an indirect proxy of vegetation and could provide insight into vegetation conditions before and after fire events.

2.4.5 Geochronology

^{14}C and optically stimulated luminescence (OSL) dating are two commonly applied and established techniques that are powerful chronometers. The application of ^{14}C method to establish a reliable chronology has been widely used through palaeoenvironmental reconstructions (Lee et al. 2011; Long et al. 2011). However, it cannot be used for organic material older than ~40 ka and can be complicated by contamination from old sources of carbon in the environment (Rittenour 2008; Long et al. 2011). ^{14}C dating can also be problematic in fluvial environments due to erosion and reworking. OSL dating has been shown to be useful in dating fluvial Quaternary sediments well-beyond the 40 ka limit of ^{14}C to the upper age limits ~200 ka (Madsen and Murray 2009; Sloss et al. 2013). OSL dating is an absolute dating technique that estimates the time when sediments (i.e. quartz and feldspar mineral grains) were last exposed to sunlight (Aitken 1998). Sunlight exposure releases electrons from light-sensitive traps in the crystal lattice, thus resetting the OSL signal (Olley et al. 1999). Once buried they accumulate signal (electrons) due to radiation emitted from decaying radionuclides in the surrounding sediment and ionizing radiation from cosmic rays (Aitken 1998; Olley et al. 1999). Burial time can be calculated by measuring the burial dose stored in the mineral grains divided by the dose rate (i.e. radiation received during burial) (Aitken 1998; Olley et al. 1999).

In fluvial environments, incomplete bleaching of quartz grains (where the signal is not fully reset during transport prior to burial) can present a challenge for OSL. However, using single-grain OSL which allows incompletely bleached grains to be identified, as well as applying the minimum age model, which reduces the influence of grains that are likely to be incompletely bleached, can minimise this problem and provide reliable age estimates. Single-grain aliquots allows for a more

accurate estimate of the OSL signal by individually measuring the grains for the equivalent dose, plus grounds for accepted or rejecting unreliable data. Whereas multiple aliquot measurements have an averaging effect, which can overestimate the ages due to varying number of grains on the disk (Jacobs and Roberts 2007; Duller 2008).

2.5 Summary

Fire occurrence in wetlands would seem like a contradiction at first, because these types of environments are often regularly inundated or saturated which would negate fire activity. However, this is not always the case, since wetlands also have high biomass to act as fuel and fire is common in wetlands that exhibit hydrological variability (i.e. distinct wet and dry periods) (Watts et al. 2015). Accessing the long-term fire history record allows us to put into perspective trends that have occurred in the past, to contextualise the contemporary setting, and begin to understand or model future impacts of fire activity. The resilience of these systems could be tested under an already changing climate, which will in turn exacerbate the severity, intensity and frequency of fires in the future, posing additional complex issues for natural resource management (Colloff and Baldwin 2010; Moritz et al. 2012). However, there has been little research considering fire history in wetlands of semi-arid drylands despite the significance of fire in these types of environments, which threatens key native terrestrial and aquatic species, and overall, ecosystem resilience. This could partly be due to the extremely complex nature of inland floodplain environments, where multi-channelled systems distribute and re-work charcoal and sediments during and shortly after (or even many years) after a fire event (Millspaugh and Whitlock 1995; Whitlock et al. 2003).

Establishing palaeoenvironmental and palaeofire histories in wetlands can be achieved using an ensemble, multi-proxy approach. These approaches can give a unique insight into past environment and fire histories, and the impacts of anthropogenic change, of which there is a particular dearth of research in semi-arid regions of eastern Australia. A knowledge gap also exists for fire history records in floodplain wetlands, and the addition of fire records could add a critical perspective for management of these generally resilient, but sometimes fragile, ecosystems.

Chapter 3 Using charcoal and environmental proxies to understand fire history and wetland conditions in the Macquarie Marshes

This chapter has been written as a manuscript for submission to a peer-reviewed journal. References and supplementary material referred to in the paper are provided at the end of the thesis.

3.0 Abstract

Fire plays an important role in floodplain wetlands, and wetland ecosystems respond dynamically in space and time to flooding, fire and geomorphological processes. Fire-climate-hydrology-vegetation interactions are complex and a multifaceted approach is required to understand and interpret fire history. This study investigated the use of macro-charcoal to interpret palaeo-fire regimes in the Macquarie Marshes. Satellite imagery showed that Buckiinguy Swamp experienced 33 ignition points from 2002-2016, whereas Willancorah Swamp experienced 6 ignition points in this period. Macro-charcoal in contemporary sediment from Buckiinguy was used to estimate fluvial charcoal supply from upstream (13.5 ± 3.2 no. cm^{-3}). Despite taking account of fluvial inputs, macro-charcoal in sediment profiles from both wetlands was highly variable. Buckiinguy had macro-charcoal up to 90 no. cm^{-3} in the upper 40 cm (mean charcoal accumulation rate; CHAR 0.55 cm^{-2} a^{-1}), and Willancorah had up to 450 no. cm^{-3} in the upper 60 cm (CHAR 3.75 cm^{-2} a^{-1}). Sedimentology, geochemistry, and carbon stable isotopes ($\delta^{13}C$ range -15 to -25 ‰) were similar in both wetlands and quite uniform with depth. When combined with charcoal records, these proxies cannot be used with confidence to reconstruct local fire regimes. Water and wetland management could benefit from future palaeo-fire research if sufficient spatial and temporal assessment of fire and wetland conditions can be achieved.

3.1 Introduction

The Australian environment has some of the most naturally susceptible and anthropogenic fire-prone landscapes on Earth (Russell-Smith et al. 2007; Bradstock et al. 2012). Fire is a significant disturbance agent that can have impacts on both terrestrial flora and fauna, landscape stability, biogeochemical cycles, and human society (Bowman et al. 2009). Developing palaeofire records allows modern fires to be placed in a long-term context, allowing fire management plans to be developed and adjusted accordingly (e.g. NPWS 1999). Knowledge of past fire regimes can also provide insights into past environmental conditions, such as periods of variability and change in climate (e.g. El Niño Southern Oscillation), hydrology and ecology (Fletcher et al. 2015; Mariani et al. 2016). For example, climate variations tend to affect vegetation distribution and composition which ultimately alters fire and fuel dynamics across the landscape (Bradstock et al. 2012). Using

charcoal and other environmental proxy records to provide information on interactions between fire, hydrology and vegetation is also critical in sensitive ecosystems (Mooney et al. 2011; Fletcher et al. 2014; Stahle et al. 2016). To unlock information about long-term fire dynamics, preservation of particulate charcoal must occur in depositional environments, for example, in lakes and wetlands (Whitlock and Anderson 2003). Furthermore, to place contemporary fire regimes and environmental conditions into a longer-term context and to assess anthropogenic impacts on fire, the sediment records also need to extend beyond the influence of past anthropogenic activity (Wilkins et al. 2013).

Macroscopic charcoal (macro-charcoal; sieve size particles >125 µm) has been widely used as a proxy to reconstruct palaeo-fire regimes as it can provide a direct line of evidence to biomass burning in the environment (Whitlock and Larsen 2001; Black et al. 2006; Burrows et al. 2014; Stevenson et al. 2015). Macro-charcoal preserved in sediment profiles, often expressed as charcoal accumulation rate (CHAR), is considered to be an indicator of local fire activity (Whitlock and Millspaugh 1996; Clark et al. 1998). This is based on the underlying assumption that macro-charcoal is the primary charcoal deposited during or shortly after a fire event (peak component), which is rapidly transported and deposited shortly after fire event into a waterbody (Clark and Royall 1996; Long et al. 1998). In contrast, secondary charcoal (often taking the form of micro-charcoal; sieve size particles <125 µm) is the background component introduced to sediment records from afar or during non-fire events by fluvial deposition (e.g. surface run-off), sediment mixing (e.g. bioturbation), or aeolian deposition (e.g. thermal convection or wind) (Clark 1988a; Whitlock and Millspaugh 1996; Clark et al. 1998). In some cases, however, macro-charcoal can originate from both local and regional (or catchment) sources, suggesting that more complex source-sink processes, depositional conditions and taphonomic processes may be at work (e.g. Oris et al. 2014).

Wetlands, including lakes, tend to act as sediment basins by accumulating and storing inorganic matter (e.g. minerals) and organic matter (e.g. charcoal) over time, making them suitable archives for palaeo-environmental research (Power et al. 2010). Most palaeo-fire research has used macro-charcoal in combination with other environmental proxies, and has been conducted in small, closed-system wetlands with permanently inundated waterbodies situated in high-elevation areas (Haberle 2005; Black et al. 2008; Buckman et al. 2009; Fletcher et al. 2014). This is because these sites are considered to be highly stable and to have high charcoal preservation potential and fairly consistent depositional histories (Conedera et al. 2009). In open-systems such as rivers or floodplain wetlands, measuring and understanding the relationships between charcoal production, transport, deposition and preservation is often more challenging (Whitlock and Larsen 2001). While it may be

straightforward to distinguish particulate charcoal size in open-systems, it cannot be assumed that macro-charcoal is always a direct indicator of local fire activity due to the possibility of external inputs from the upstream catchment (Clark and Royall 1996; Carcaillet et al. 2001) . Differences in environmental conditions between small, stable closed-systems and large, fluvial and/or dynamic open-systems can further complicate interpretation of fire history in the landscape, and so factors such as catchment size and morphology, stream inputs or outputs, and vegetation types need to be considered (Power et al. 2010).

Wetlands in large catchments can be profound recorders of long-term environmental change, but they can buffer short-term events, creating a lag time between the cause and effect within the system, including sediment delivery and water level response (Willams et al. 1998). These systems respond to large-scale external catchment controls (e.g. catchment geology, valley confinement, climatic conditions) and internal factors (e.g. downstream changes in discharge and sediment transport) which affect river behaviour and character (Tooth 2000). Furthermore, large catchments with dynamic rivers and wetlands often have complex hydrology and inundation patterns, and fire can be highly variable in space and over time. This means that identifying sources of primary charcoal (i.e. local) and secondary charcoal (i.e. regional) production from within the wetland and elsewhere in the catchment can be problematic. This is particularly true for floodplain wetlands in semi-arid and arid catchments (i.e. wetlands in drylands; WIDS). These systems have low, variable rainfall, high evapotranspiration, highly variable flooding and long droughts leading to mosaic-like geomorphology and vegetation (Tooth and McCarthy 2007; Ralph and Hesse 2010). Although periods of increased fire activity may represent periods with higher fuel loads (i.e. greater biomass), or greater ignition potential, or more intense burning (Black et al. 2007), it can be difficult to disentangle a fire signal from ‘background noise’ in WIDS if charcoal comes from multiple sources. Floodplain wetlands with numerous anastomosing and/or distributary channels also have inherently complex geomorphological processes (Tooth and McCarthy 2007). Understanding the complexity of wetlands, as well as the potential sources of charcoal and processes of charcoal transportation, reworking and deposition is critical for efforts to reconstruct fire activity and interpret fire regimes (Whitlock and Millspaugh 1996; Whitlock and Anderson 2003; Power et al. 2010).

3.2 Research question and aims

The Macquarie Marshes are a large, Ramsar-listed, freshwater floodplain wetland system in southeastern Australia which has never been studied in terms of its long-term fire history or the lasting impacts of fire in the wetlands. Nevertheless, management agencies are fully aware of the need for additional information to address pressing environmental issues such as fire in wetlands of

high-conservation value, including the Macquarie Marshes (OEH 2012; Berney and Hosking 2016). NSW government records show that since 1947 there have been 18 known major wildfires in and adjacent to wetlands in what is now the Macquarie Marshes Nature Reserve (OEH 2012), however there is no long-term record of fire activity to place these recent fire events in context.

In this paper that main research question that will be addressed is *"Can macro-charcoal combined with other environmental proxies be a reliable indicator of past fire activity in the Macquarie Marshes?"* The aims of the research are to:

1. Determine whether there an interpretable fire history in the sediment profiles of Buckiinguy and Willancorah Swamps based on analysis of macro-charcoal in sediment.
2. Measure the type and amount of fluvial charcoal entering the system from upstream to distinguish a background of macro-charcoal supply from *in situ* macro-charcoal in sediment cores linked to wetland fire history.
3. Examine whether macro-charcoal, combined with other environmental proxies, can provide evidence of a fire regime in the wetlands, which may then help guide future fire management.

3.3 Study area and field sites

The Macquarie Marshes (30° 45' S, 147° 33' E) has a diverse network of river channels and permanent, intermittent and ephemeral wetlands located on the lower reaches of the Macquarie River, New South Wales (Figure 1). The wetland system covers an area of >2,000 km^2 when inundated during large floods, and is situated in a semi-arid climate zone (Köppen classification BSh) with mean annual rainfall ~442 mm and mean annual evapotranspiration >2,000 mm (Quambone rainfall gauge 051042) (Bureau of Meteorology 2017).

The geomorphological record of the Macquarie Marshes reveals a long history of channel formation and abandonment due to avulsion (the process of channel relocation on the floodplain) driven by sedimentation and erosion, as well as wetland adjustment resulting from changes in inundation and ecosystem processes (Ralph et al. 2011). The wetlands feature extensive areas of common reed (*Phragmites australis*), water couch (*Paspalum distichum*) grassland, and river red gum (*Eucalyptus camaldulensis*) woodland and forest that are reliant on overbank and overland flooding from numerous channels (Yonge and Hesse 2009; Ralph and Hesse 2010). The wetlands provide essential habitat and refuge for a wide range of flora and fauna (Kingsford and Auld 2005; OEH 2012). The Macquarie Marshes Nature Reserve (MMNR) is concentrated on two core areas in the southern and northern parts of the system, which comprise ~10 % (~219 km^2) of the total

wetland area. The MMNR is recognised under the Ramsar Convention for its international ecological significance, namely a prime location for migratory, colonial and endangered waterbirds (Kingsford and Auld 2005; Bowen and Simpson 2010; OEH 2012).

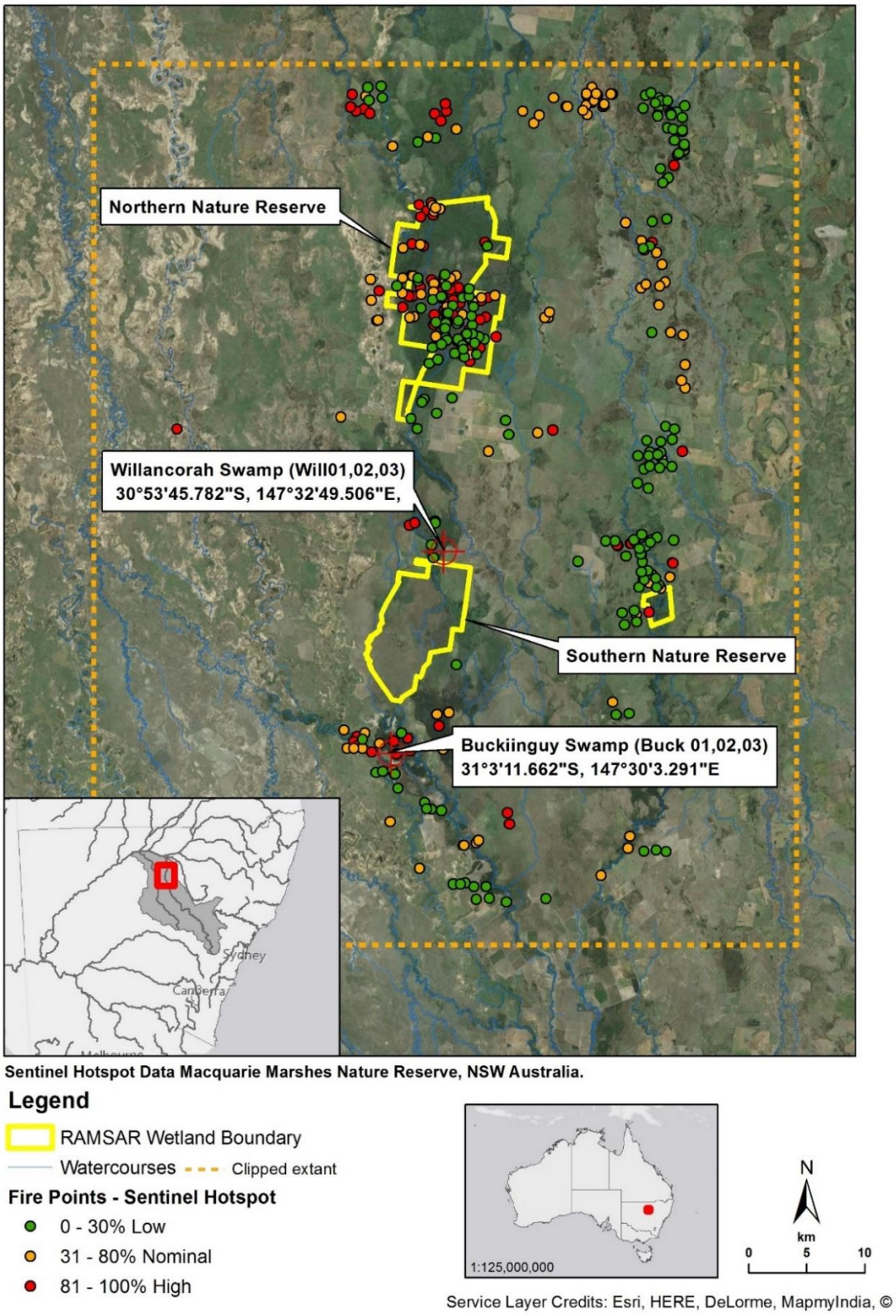

Figure 1: Location of Buckiinguy Swamp and Willancorah Swamp in the Macquarie Marshes, New South Wales, Australia, with Sentinel Hotspot data from 2002-2016 (Geoscience Australia 2017).

The Macquarie Marshes have been the focus of much research on hydrology (Kingsford and Johnson 1998; Kingsford 2000; Thomas et al. 2011) , ecology (Kingsford and Auld 2005; Kobayashi et al. 2011; Kobayashi et al. 2015; Whitaker et al. 2015; Yu et al. 2015), geomorphology (Yonge and Hesse 2009; Ralph and Hesse 2010; Ralph et al. 2016), and environmental management (Thoms and Sheldon 2002; Berney and Hosking 2016). However, very little is known about the fire history in this system despite the probability of a long history of Aboriginal burning (Balme and Beck 1996) and the fact that fire has been used by pastoralists in the post-settlement period for the management of wetland vegetation and to promote regrowth for cattle and sheep grazing (NPWS 1999). Of the 18 major wildfires since 1947 in and adjacent to the MMNR, four of the largest fires (1947, 1966, 1994 and 1995) burnt >10 km^2 of reed beds, grassland and riverine woodlands in the northern Macquarie Marshes (NPWS 1999; OEH 2012). These events were perceived as being rare, since seasonal flooding did not occur in these years due to the onset of a drought conditions (NPWS 1999). However prior to 1960s and before the effects of river regulation (e.g. the construction of Burrendong Dam in 1967), fires occurred every one or two years but they were typically short-lived and burnt out within few days partly due to the sub-surface moisture protecting the roots and reedbed (OEH 2012).

The two field sites for this study are Buckiinguy Swamp and Willancorah Swamp in the southern Macquarie Marshes, both just outside the Ramsar-listed MMNR (Figure 1). These wetlands are key ecological assets under private ownership and they support a variety of key semi-permanent and flood-dependant vegetation (Bowen and Simpson 2010; DECCW 2010). Both wetlands are susceptible to burning by fire. Buckiinguy Swamp is a floodout-style wetland at the end of Buckiinguy Creek, which is a distributary channel of the Macquarie River. The wetland has built up on top of sediment laid down by the Macquarie River and is mainly occupied by a small reed bed with water couch grassland and river red gum woodland at its margins (Figure 2A, B). Buckiinguy Creek begins to break down (terminate) as it flows into the reed bed due to overbank water loss and sedimentation in the channel and the wetland, and small channels on the northern perimeter drain water back into the Macquarie River (Yonge and Hesse 2009). Willancorah Swamp is also a floodout-style wetland with a large reed bed, water couch grassland and some river red gum woodland (Figure 2C, D). This wetland is fed by Monkeygar Creek, previously a distributary channel of the Macquarie River and now the main branch of the river in the southern Macquarie Marshes (Yonge and Hesse 2009; Ralph et al. 2011). Monkeygar Creek breaks down into Willancorah Swamp for the same reasons as Buckiinguy – a loss of flow and sediment transport efficiency – and has several channels flowing north and back into the Macquarie River.

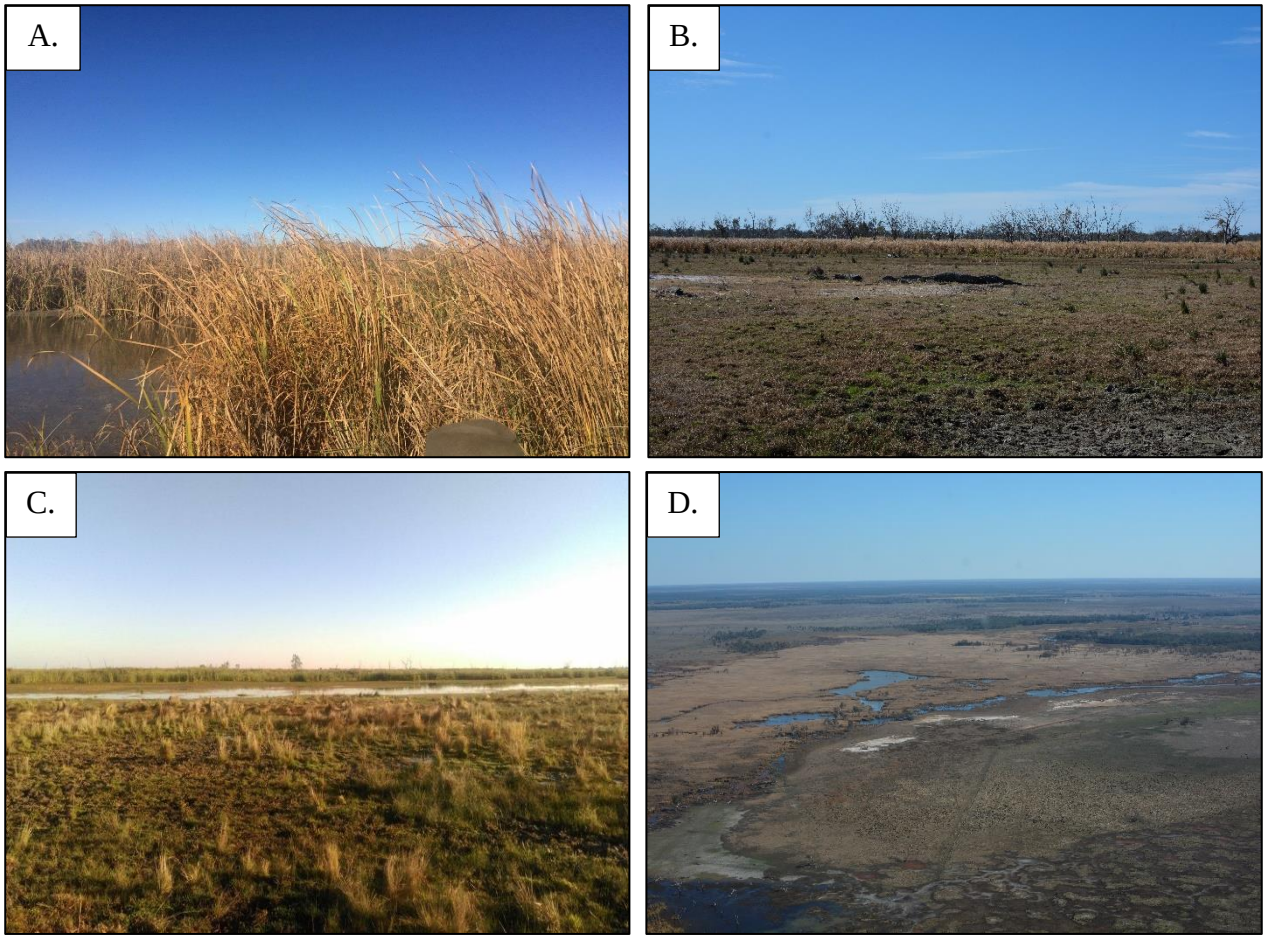

Figure 2: (A) Reed bed in Buckiinguy Swamp (B) water couch grassland on the periphery of Buckiinguy Swamp (C) reed bed and water couch grassland near Willancorah Swamp and (D) aerial view of Willancorah Swamp looking northwest.

3.4 Methods

3.4.1 Fire ignition hotspot mapping

Conservative mapping and spatial analysis was conducted on recent ignition points from 2002-2016 in the Macquarie Marshes was performed using the Geoscience Australia Sentinel Hotspot database, part of the national bushfire monitoring system of Australia. Sensors on the satellite measure the radiative power (MW km^{-2}) of fires which are then assigned a confidence level where: 0-30 % is 'Low'; 30-80 % is 'Nominal' and >80 % is 'High' (Giglio et al. 2003; Geoscience Australia 2016). Ignition points (hereafter referred to as fire) data related to these three levels of confidence of possible fire activity are presented in this study without further data post-processing.

3.4.2 Sediment core collection and sampling

Fieldwork was conducted in December 2016 and July 2017 at Buckiinguy Swamp and Willancorah Swamp in the southern Macquarie Marshes. At both times, the wetlands were partially

inundated by flooding which began with a series of events during the winter-spring of 2016, a period which saw above average rainfall and river flows (OEH 2017). Sediment core collection was restricted to the margins of both swamps where water was shallow, and although both swamps showed signs of stock grazing, coring sites were chosen carefully to be representative of the wetland and with minimal disturbance. Three cores were extracted from each of the wetlands using a steel core barrel with a PVC pipe insert that was manually driven into the ground and extracted intact. For Buckiinguy, Buck01 (0-60 cm) and Buck02 (0-55 cm) were replicate cores situated immediately next to each other near the margin of the water couch grassland. Buck03 (0-85 cm) was a core previously sampled from the centre of the Buckiinguy reed bed (Ralph 2001) that was kept fully sealed, wrapped and refrigerated for further research until 2017. For Willancorah, Will01 (0-60 cm) and Will02 (0-60 cm) were replicate cores situated immediately next to each other, while Will03 (0-120 cm) was taken in the reeds ~17 m west of Will02. All sediment cores were sealed in PVC pipe and were not opened or exposed to sunlight. All were carefully transported back to Department of Environmental Sciences at Macquarie University and stored in a fridge at 4 °C until they were ready for sub-sampling for charcoal, sedimentological, geochemical and geochronological analysis.

Buck01 and Will01 were used only for OSL dating, while Buck02, Buck03, Will02 and Will03 were described and sub-sampled for all other analyses (Appendix 1). Contiguous 2 cm^{-3} sub-samples were taken along the entire length of each core using a plastic syringe at 1.5 cm intervals to provide sub-samples for further analysis. One half of each core was kept intact for ITRAX core scanning (see section 3.4.7), before any sub-sampling was undertaken.

3.4.3 Fluvial sediment and charcoal sampling

In a previous study, synthetic grass mats (surface area 0.4 m^2) were anchored to the ground in the wetlands adjacent to Buckiinguy Creek and in Buckiinguy Swamp prior to an environmental flow and a series of small floods which caused inundation for 9 months in 2009-2010 (Ralph et al. 2012). No fires occurred during this period of sediment sampling. The mats were installed to trap contemporary fluvial sediment being washed into the wetlands at four sites in Buckiinguy Swamp: B1, ~2 km upstream of the reed bed; B2, 0.25 km upstream of the reed bed; B3, at the entry to the reed bed, and; B4, at the downstream edge of the reed bed. Each site had three sampling intervals at increasing distances away from the channel (e.g. 2 m ,10 m, 50 m) and at each interval mats were laid in a 2 x 2 m grid (i.e. 4 mats per interval, 3 intervals per site, 4 sites; n=48). After 9 months of inundation the mats were collected and the fluvial sediment deposited and trapped on the mats was extracted, weighed and dried for analysis (Ralph et al. 2012). For this present study, macro-charcoal

was extracted from the fluvial sediment samples using standard methods (see section 3.4.5 below). After calculating the concentration of macro-charcoal in each fluvial sample, the mean was determined (expressed as no. cm^{-3}) and multiplied by the mean dry bulk density of the sediment cores from Buckiinguy and Willancorah Swamp to determine the mean value (and standard error) of fluvial macro-charcoal entering from upstream (expressed as no. cm^{-3}). This 'fluvial background' was then subtracted from the total concentration of macro-charcoal recorded for each of the sediment cores to isolate the *in situ* macro-charcoal signal potentially related to local fires in the wetlands.

3.4.4 Sedimentology

Cores Buck02, Buck03, Will02 and Will03 were used for sedimentology. Water content was determined by drying and weighing sub-samples using standard methods. Sand and mud content were determined by sieving dry sub-samples at 63 µm to determine the >63 µm (sand) and <63 µm (mud) fractions. Samples were dried at 105 °C for 24 hours and dry bulk density (DBD) was determined using methods in Blake and Hartge (1986). Loss-on-ignition (LOI) was performed at 550 °C to determine organic matter content (LOI_{550}), and at 950 °C to determine inorganic matter (carbonate) content (LOI_{950}) using standard methods in Rayment and Lyons (2011).

3.4.5 Charcoal extraction and analysis

Cores Buck02, Buck03 and Will02, Will03 were split-longitudinally and sub-sampled at 1.5 cm intervals for charcoal analysis. The macro-charcoal extraction, dispersal and counting procedure followed Stevenson and Haberle (2005), where sub-samples of ~2.26 cm^{-3} were sampled contiguously using a plastic syringe at 1.5 cm intervals along the entire core length. Sediment sub-samples were then dispersed in sodium hexametaphosphate to disaggregate the charcoal and sediment, and placed in a mechanical end-over-end mixer for 24 hours. After chemical and physical disaggregation, the dispersant was decanted and the sub-samples were re-suspended in dilute 5 % hydrogen peroxide for 24 hours. The sub-samples were then sieved at 250 and 125 µm using RO water, and the remaining material transferred into vials according to the size fraction (>250 µm and 125-250 µm). Sub-samples were individually placed onto a petri dish under a binocular microscope at 10x5 magnification (see Appendix 2). Macro-charcoal was identified as black, opaque, shiny and angular particles, and all particles were manually counted on a petri dish with labelled segments (1-8). Where the abundance of charcoal was too high or when organic and sediment material made counting too difficult, four segments randomly selected were counted and the counts doubled. The macro-charcoal concentration of both >250 µm and 125-250 µm fractions was assessed independently then combined to calculate the total macro-charcoal concentration (>125 µm; no. cm^{-}

^{3}). Mean charcoal accumulation rates (CHAR; no. cm^{-2} a^{-1}) were calculated by multiplying the charcoal concentrations by the mean sedimentation rate derived from OSL dating (section 3.4.8).

3.4.6 Stable isotope analysis

Physical and chemical treatment was performed on Buck03 and Will03 cores for carbon stable isotope ($\delta^{13}C$) and total carbon (C %) analysis at the Australian Nuclear Science and Technology Organisation (ANSTO) using standard methods. Samples were prepared with 1M HCl to remove carbonates prior to $\delta^{13}C$ analysis, and then analysed using an Elementar VarioMICRO Elemental Analyser and an IsoPrime Continuous-Flow Isotope Ratio Mass Spectrometer (CF-IRMS) to quantify the variations of carbon isotopes. The results are reported as $\delta^{13}C$ values in parts per thousand (‰ or 'per mil'), where $\delta^{13}C$ refers to the ratio of ^{13}C:^{12}C relative to an internationally defined scale Vienna Pee Dee Belemnite standards (VPDB). Total carbon analysis was performed separately on an untreated sub-sample using the same machine as mentioned above.

3.4.7 Sediment geochemistry

Sediment geochemistry was analysed using ITRAX high-resolution core scanning and micro-X-ray fluorescence (micro-XRF) spectrometry at ANSTO. The Cox Analytical System ITRAX system provides high-resolution optical images, X-radiographs, geochemical and magnetic susceptibility profiles. The technique is non-destructive and provides data as counts which are considered semi-quantitative values for elemental composition (Croudace et al. 2006). The resolution for the X-radiograph was 500 µm and the XRF analysis was 1000 µm. Magnetic susceptibility was measured at 5 mm intervals. All results were processed using Q-Spec software and normalised by the total counts to correct for porosity and matrix (Bouchard et al. 2011). Statistical analysis was carried out using RStudio to obtain principal component analysis (PCA).

3.4.8 Geochronology

A chronology for the sediment cores from Buckiinguy and Willancorah Swamp was established using optically-stimulated luminescence (OSL) dating at Macquarie University's 'Traps' luminescence dating facility. The cores Buck01 (equivalent to Buck02), Buck03, Will01 (equivalent to Will02) and Will03 were all split longitudinally and sub-sampled under subdued red-light conditions. Sub-samples were wet-sieved to isolate the 90-212 µm fraction required for dating, while the <90 µm and >212 µm fractions were stored. Standard methods were used to dissolve carbonate with HCl and organic materials with H_2O_2, to remove heavy minerals and feldspars using sodium polytungstate density separation at 2.7 and 2.62 g cm^{-3} respectively, and to etch quartz

grains in 40 % hydrofluoric acid for 45 minutes to remove alpha irradiated outer surface of the quartz grains (Aitken 1998).

Prior to single-grain analysis, preheat and dose response tests were conducted to determine the optimal measurement conditions for these samples. The preheat procedure removes charge from the thermally unstable shallow traps that are filled during artificial radiation, so the selection of an appropriate temperature can have a significant effect on the equivalent dose determination (Huntley et al. 1985). From the preheat plateau and dose recovery tests a preheat temperature of 260 °C for 10 seconds was selected, and was used prior to the measurement of the natural, regenerative and test dose signals. All OSL measurements were conducted in an automated Risø TL-DA-20 reader fitted with an Electron Tubes Ltd 9635QA photomultiplier tube and 3 x U340 filters. For single-grain OSL measurements, quartz grains from the 180-212 µm fraction were mounted on a 10x10 precision drilled aluminium disk. The grains were stimulated for 2 seconds using a green 10 Mw 532 NM Nd:YVO4 solid-state diode pump laser. The single-aliquot regeneration (SAR) protocol was applied for single-grain analysis for equivalent dose determination (Galbraith et al. 1999; Murray and Wintle 2003). Acceptance and rejection of grains was based from the criteria outlined in (Jacobs et al. 2006).

The dosimetry of the sites was estimated using samples from the cores combined with cosmic ray contribution data according to Prescott and Hutton (1994), taking into account the site altitude, geomagnetic latitude and sediment overburden. The contribution from Uranium, Thorium Potassium and Rubidium was calculated using a Geiger-Muller beta counter for dried and milled sediment combined with thick source alpha counting using a Daybreak alpha counter. The equivalent dose is divided by the environmental dose rate to derive an OSL age estimate (Huntley et al. 1985; Aitken 1998). Since partial bleaching of grains that can lead to age overestimation is common in fluvial systems, the minimum age model (MAM) was applied to all single-grain OSL data to minimise the influence of partially bleached grains on the final age estimates (Galbraith et al. 1999; Murray and Wintle 2003).

3.5 Results

3.5.1 Recent fire history

Sentinel Hotspot data reveals several clusters of fire activity in both sectors of the northern and southern Macquarie Marshes (Figure 1). The northern Macquarie Marshes have had by far the greatest number of fires in the last 10 years, many of these being inside the MMNR (Figure 3). In contrast, this data shows that the southern MMNR has had no fires in the last 10 years, but that fires

have occurred adjacent to the southern MMNR in Buckiinguy and Willancorah Swamp. Buckiinguy has experienced 33 fires in the period 2002-2016 (Figure 4), while Willancorah Swamp had just 6 fires (Figure 5). At Buckiinguy, several of the high confidence fire hotspots are in close proximity to the sediment coring sites, while at Willancorah there are no fire hotspots close to the coring sites.

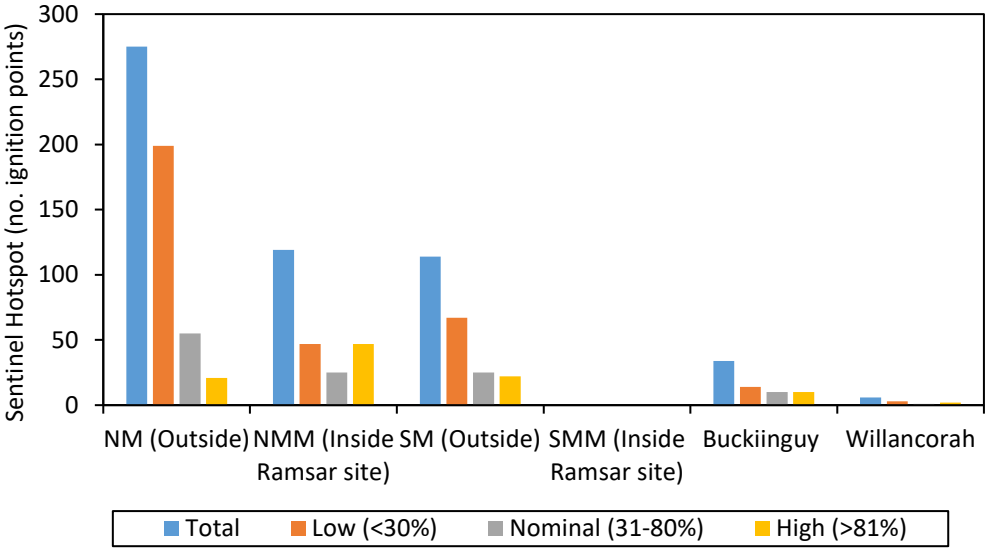

Figure 3. Summary of low, nominal and high confidence Sentinel Hotspot data from 2002-2016 for the northern and southern Macquarie Marshes. Data from Geoscience Australia (2017).

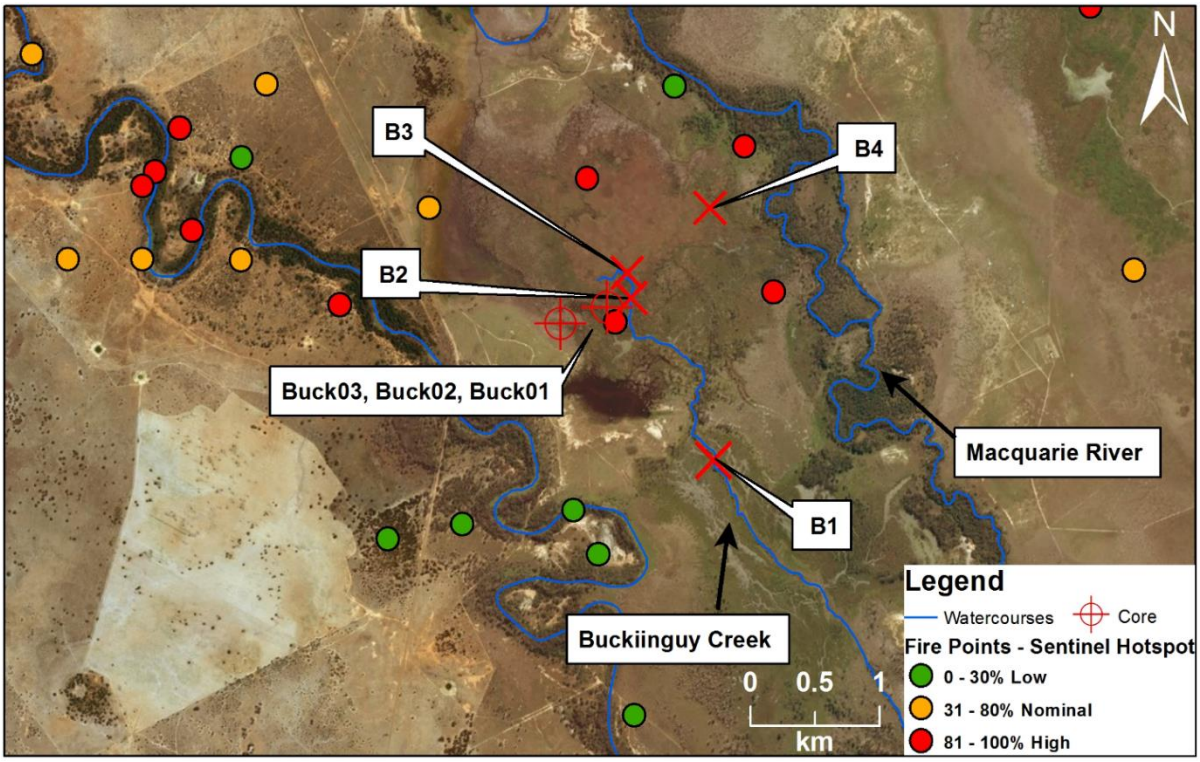

Figure 4: The spatial distribution of fire ignition points in Buckiinguy Swamp from 2002-2016. Data from (Geoscience Australia 2017).

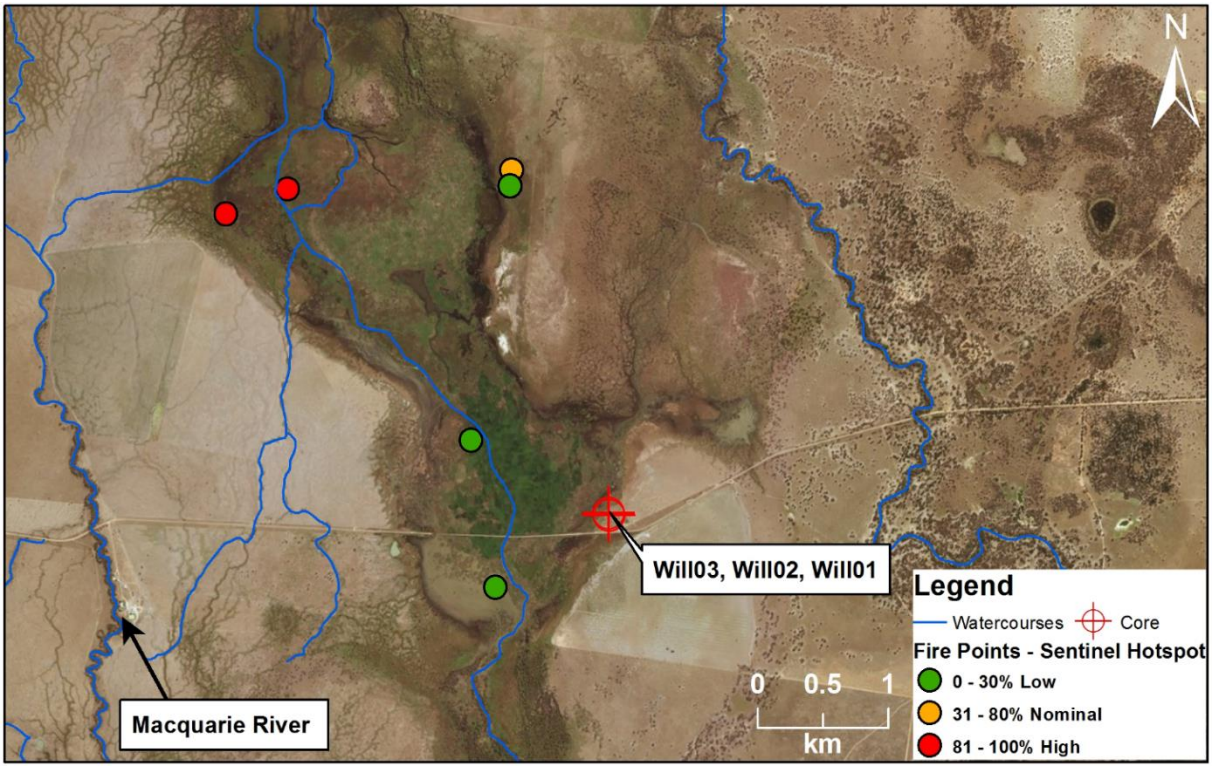

Figure 5: The spatial distribution of fire ignition points in Willancorah Swamp from 2002-2016. Data from (Geoscience Australia 2017).

3.5.2 Fluvial charcoal supply

The distribution of fine sediment trapped on synthetic grass mats in Buckiinguy Swamp during 9 months of inundation in 2009-2010 was highly variable, but some clear trends are present. Site B3 where the channel of Buckiinguy Creek enters the reed bed had the highest volume of deposited sediment, while sites B1 and B2 upstream and site B4 downstream had variable, but lower volumes of deposited sediment (Figure 6A). In contrast, all three sites leading into the reed bed (B1, B2 and B3) had consistently low concentrations of macro-charcoal in the modern deposited sediment, showing that fluvial sediment derived from the upstream catchment has a generally low concentration of macro-charcoal (Figure 6B). In contrast, site B4 had a higher and more variable concentration of macro-charcoal in the deposited sediment, possibly due to local reworking near the outlet of Buckiinguy Swamp downstream of the reed bed. Therefore, the mean and standard error of the baseline of fluvial charcoal entering the system from upstream was determined to be equivalent to 13.5 ± 3.2 no. cm^{-2} based on the data from sites B1, B2 and B3. It is also clear that there is no significant linear relationship (r^2=0.0002; p=0.95) between fluvially deposited sediment and macro-charcoal at the sites in Buckiinguy Swamp (Figure 6C).

There was also variability and some trends observed in deposited sediment and macro-charcoal at each of the sites. Samples from closest to the channel of Buckiinguy Creek had more

variable and greater volumes of deposited sediment than sites further away from the channel (Figure 7A-D). In contrast, no common trends are present for macro-charcoal concentrations with distance away from the channel. Sites B1 and B2 seem to decline slightly in macro-charcoal onto the floodplain, while site B3 an increase in macro-charcoal across the floodplain, and site B4 has a decrease in macro-charcoal with distance (Figure 7E-H). Despite the within-site variability, a conservative estimate of the fluvial background of macro-charcoal of 16.5 no. cm^{-2} (based on an upper estimate from the mean and standard error; 13.5 ± 3.2 no. cm^{-2}) can be subtracted from the total concentration of macro-charcoal found in sediment cores in the wetlands, to yield an estimate of *in situ* macro-charcoal likely related to local fires in the wetlands (Figure 8). When the fluvial macro-charcoal background is considered in the sediment cores, small peaks below the background are removed, leaving only the larger peaks in the record.

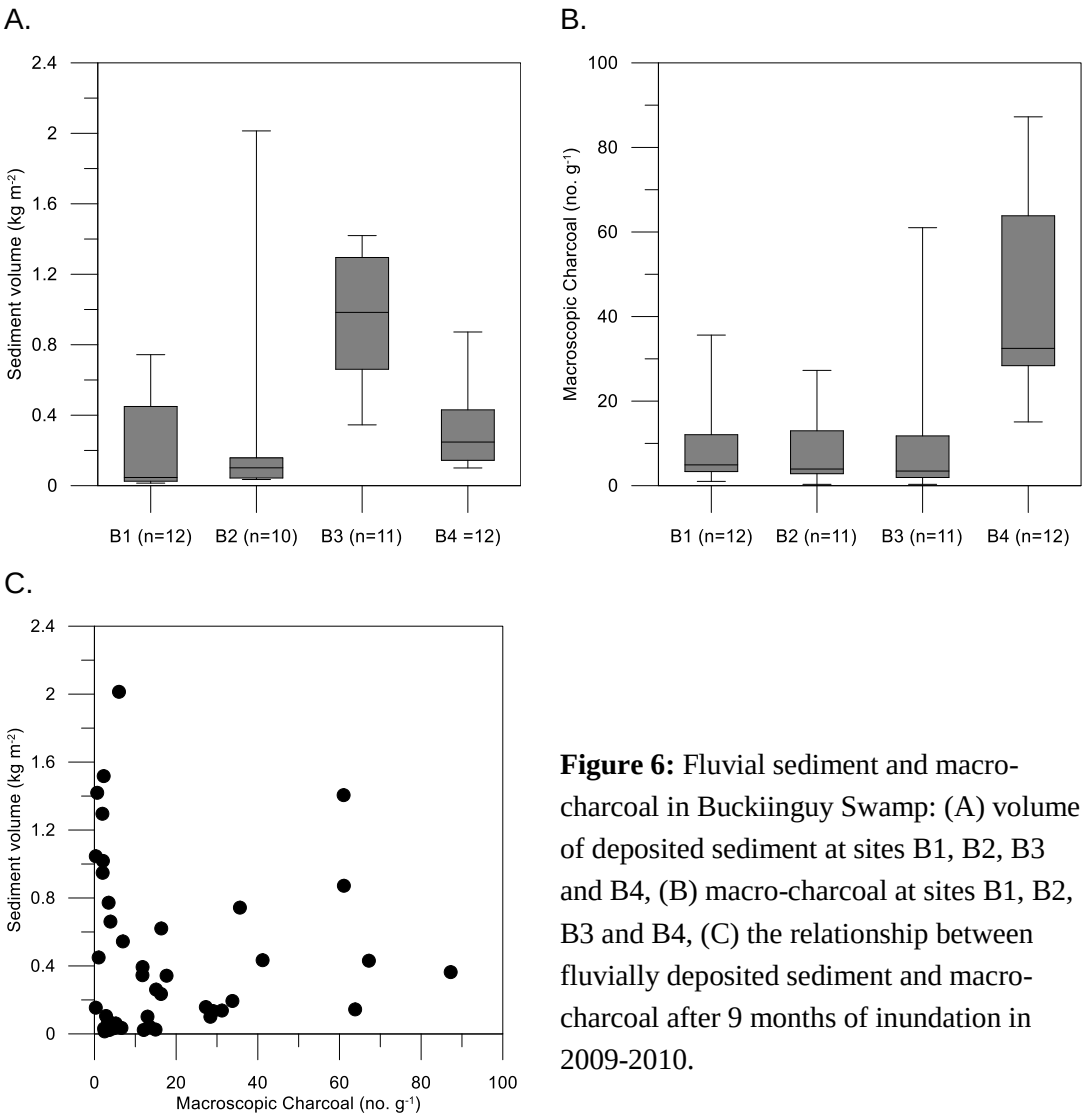

Figure 6: Fluvial sediment and macro-charcoal in Buckiinguy Swamp: (A) volume of deposited sediment at sites B1, B2, B3 and B4, (B) macro-charcoal at sites B1, B2, B3 and B4, (C) the relationship between fluvially deposited sediment and macro-charcoal after 9 months of inundation in 2009-2010.

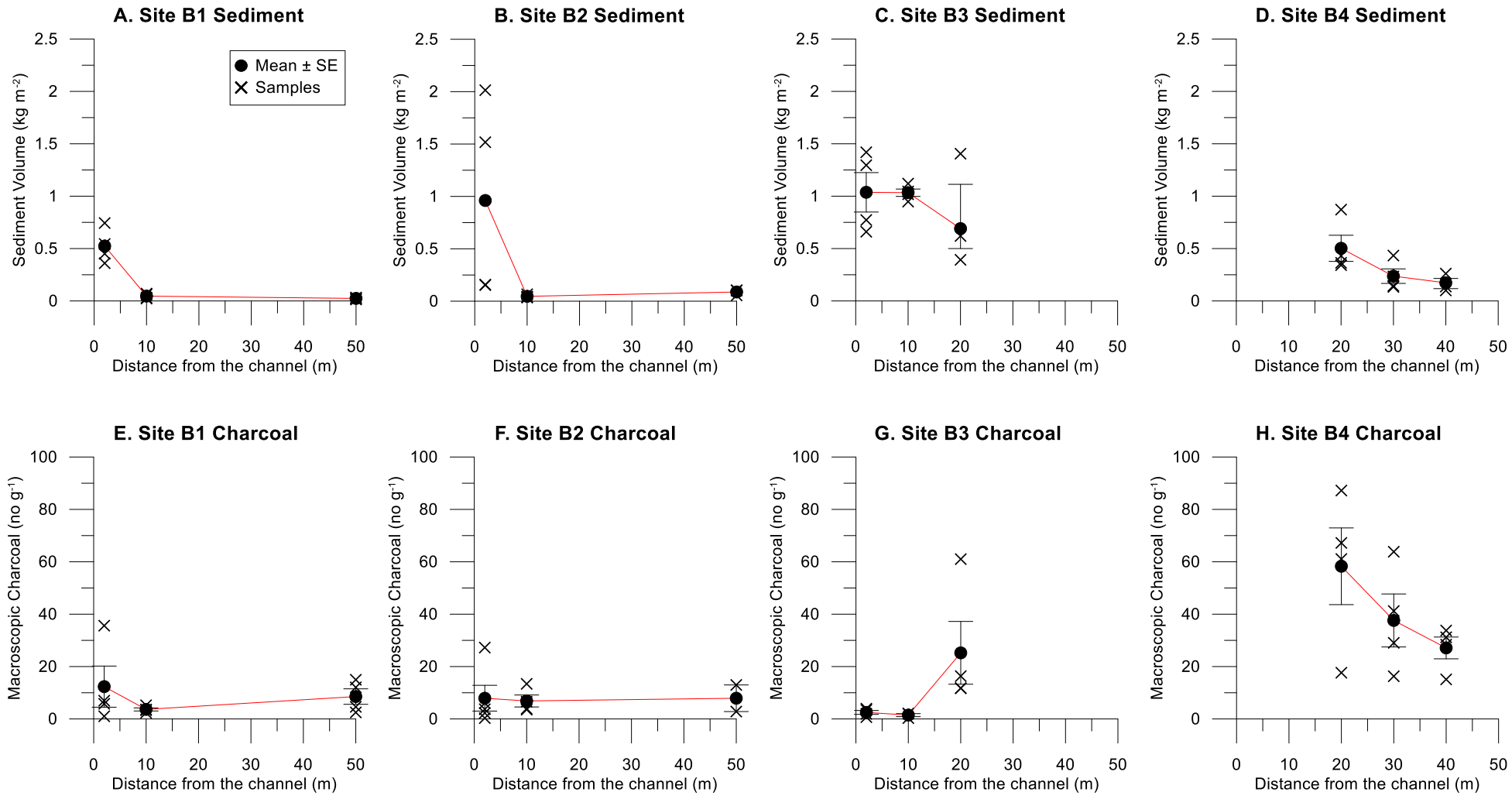

Figure 7: Volume of sediment deposited with increasing distance from the channel in Buckiinguy Swamp at (A) site B1, (B) site B2, (C) site B3 and (D) site B4, and charcoal concentration in the deposited sediment at (E) site B1, (F) site B2, (G) site B3 and (H) site B4.

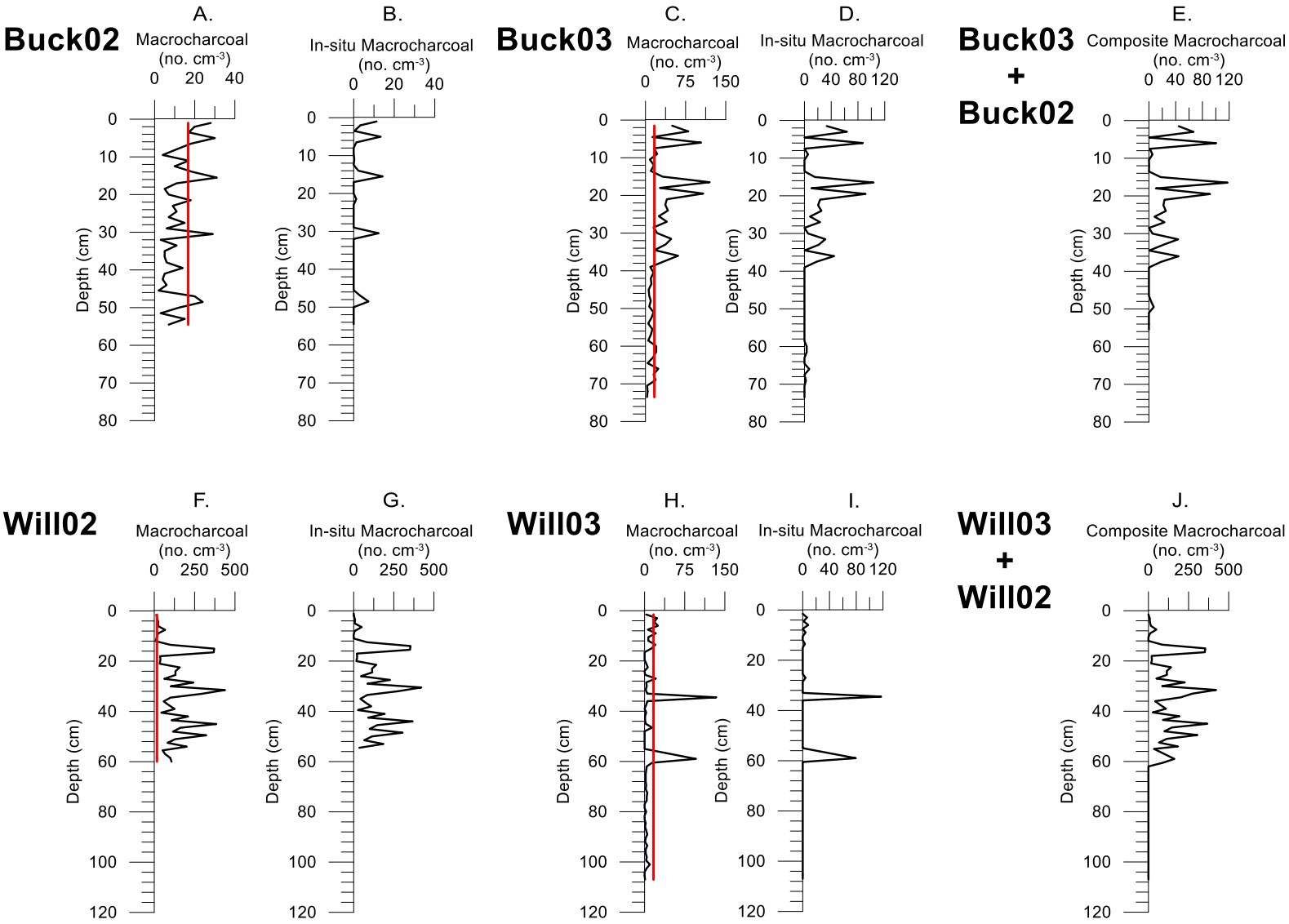

Figure 8: Macro-charcoal in cores from Buckiinguy and Willancorah Swamp, with the fluvial background concentration (red line at 16.5 no cm-3) applied to (A-B) Buck02 and (C-D) Buck03, yielding (E) a composite record; and (F-G) Will02 and (H-I) Will03, yielding (J) a composite record.

3.5.3 Sedimentology and in situ macro-charcoal

Buckiinguy Swamp cores Buck02 and Buck03 consisted of relatively organic rich, silty clay with some roots present in the upper ~10 cm, then a fine silty clay with some sand (less than 20 %) throughout the profiles to depth (Figures 9 and 10). Visible roots, charcoal fragments, manganese/iron nodules and carbonate nodules occurred throughout the profiles. Water content was greatest in the top ~10 cm (20-60 %) of the cores, while DBD was lowest near the surface and increased with depth (from 0.2 to ~2.0 g cm^{-3}). Organic matter (LOI_{550}) and carbonate (LOI_{950}) content were high in the upper ~10 cm of the profile for Buck03 (~54 % and 12 %, respectively) before decreasing with depth, but both organic matter and carbonate content were fairly uniform with depth in Buck02 (Figures 9 and 10).

Macro-charcoal concentrations are variable in both cores from Buckiinguy. Buck02 has intermittent gaps with small macro-charcoal peaks at ~5 cm, ~15 cm, ~30 cm and ~48 cm (Figure 9D). In contrast, Buck03 has consistently higher macro-charcoal concentrations throughout the upper 40 cm of the profile, with distinctive peaks at ~4 cm, ~8 cm and ~20 cm, as well as a series of smaller peaks in between (Figure 10D). The composite *in situ* macro-charcoal record for Buckiinguy using both cores is therefore dominated by Buck03, with peak macro-charcoal concentrations at 6 cm, 16.5 cm and 19.5 cm (Figure 8E).

Willancorah swamp cores Will02 and Will03 also consisted of a top organic rich, silty clay within the upper 5-10 cm, followed by a transition into a fine silty clay with sand (less than 50 %) in the lower parts of the profile (Figures 11 and 12). Water content was consistent with depth in both cores, and DBD was also similar throughout the cores (1.5 to 2.0 g cm^{-3}). Except for a peak in carbonate ~3 cm in Will03, both organic matter and carbonate content were uniform with depth in the cores.

The macro-charcoal records for Will02 and Will03 were highly variable with depth. Will02 had very high concentrations of macro-charcoal and several peaks throughout the profile between 8-60 cm (Figure 11D). In contrast, Will03 had much lower concentrations of macro-charcoal and just two peaks at ~37 cm and ~59 cm (Figure 12D). The composite *in situ* macro-charcoal record for Willancorah using both cores is therefore dominated by Will02, with peak macro-charcoal concentrations at 15 cm, 28 cm and 49 cm (Figure 8J).

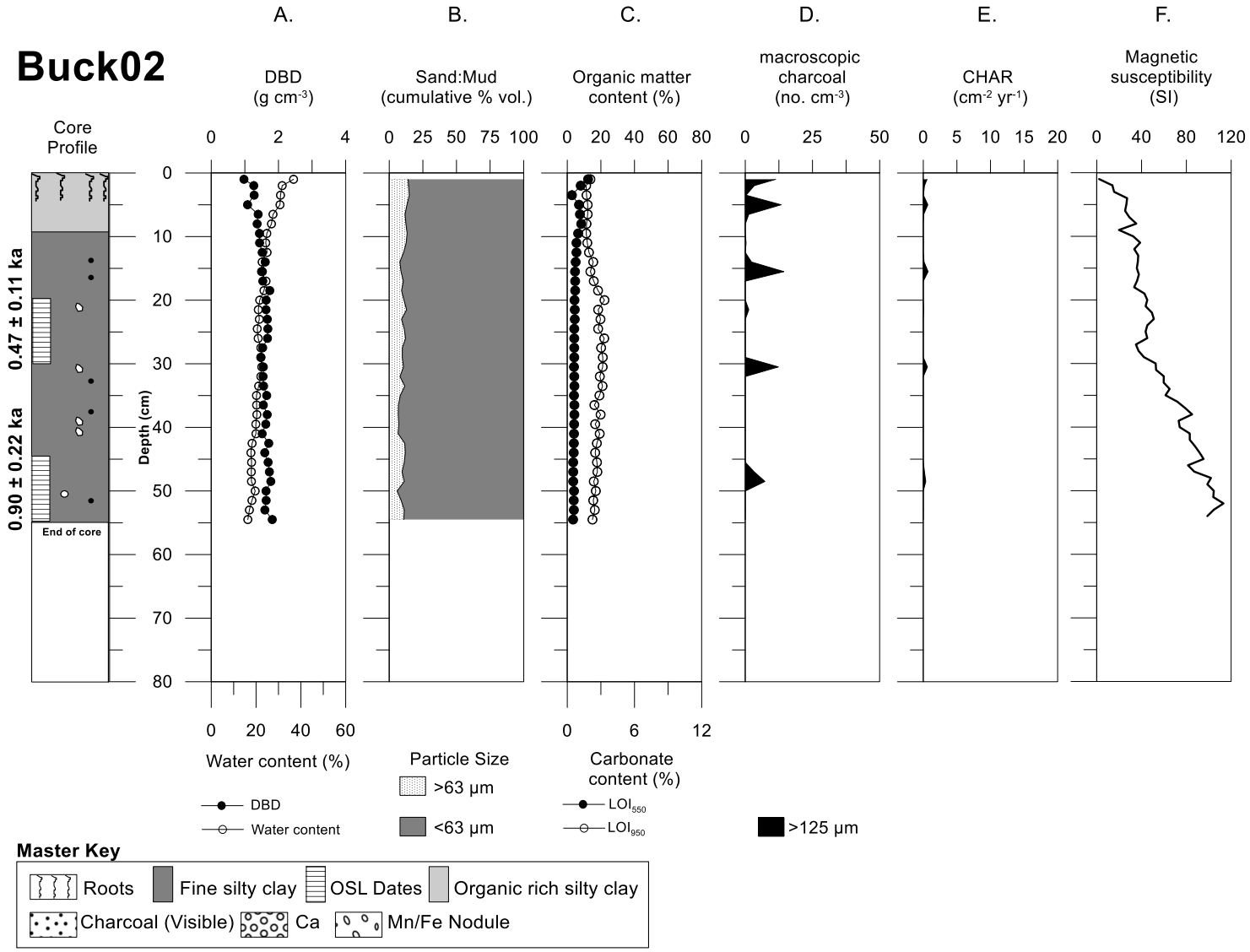

Figure 9: Detailed core description of Buck02, including (A) DBD and water content, (B) sand and mud content, (C) LOI_{550} and LOI_{950}, (D) macro-charcoal concentration, (E) charcoal accumulation rate, and (F) magnetic susceptibility.

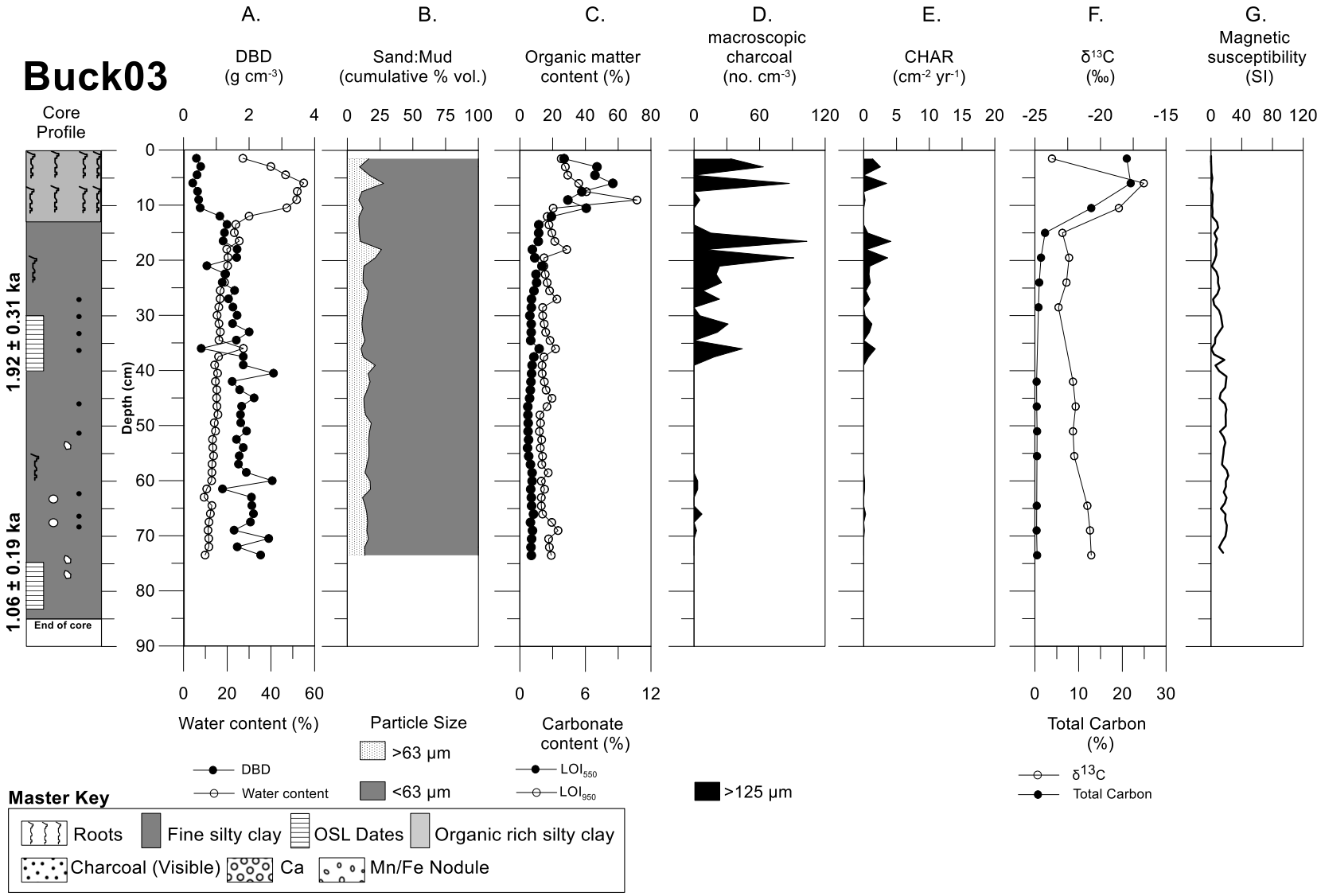

Figure 10: Detailed core description of Buck03, including (A) DBD and water content, (B) sand and mud content, (C) LOI550 and LOI950, (D) macro-charcoal concentration, (E) charcoal accumulation rate, (F) δ13C and total carbon, and (G) magnetic susceptibility.

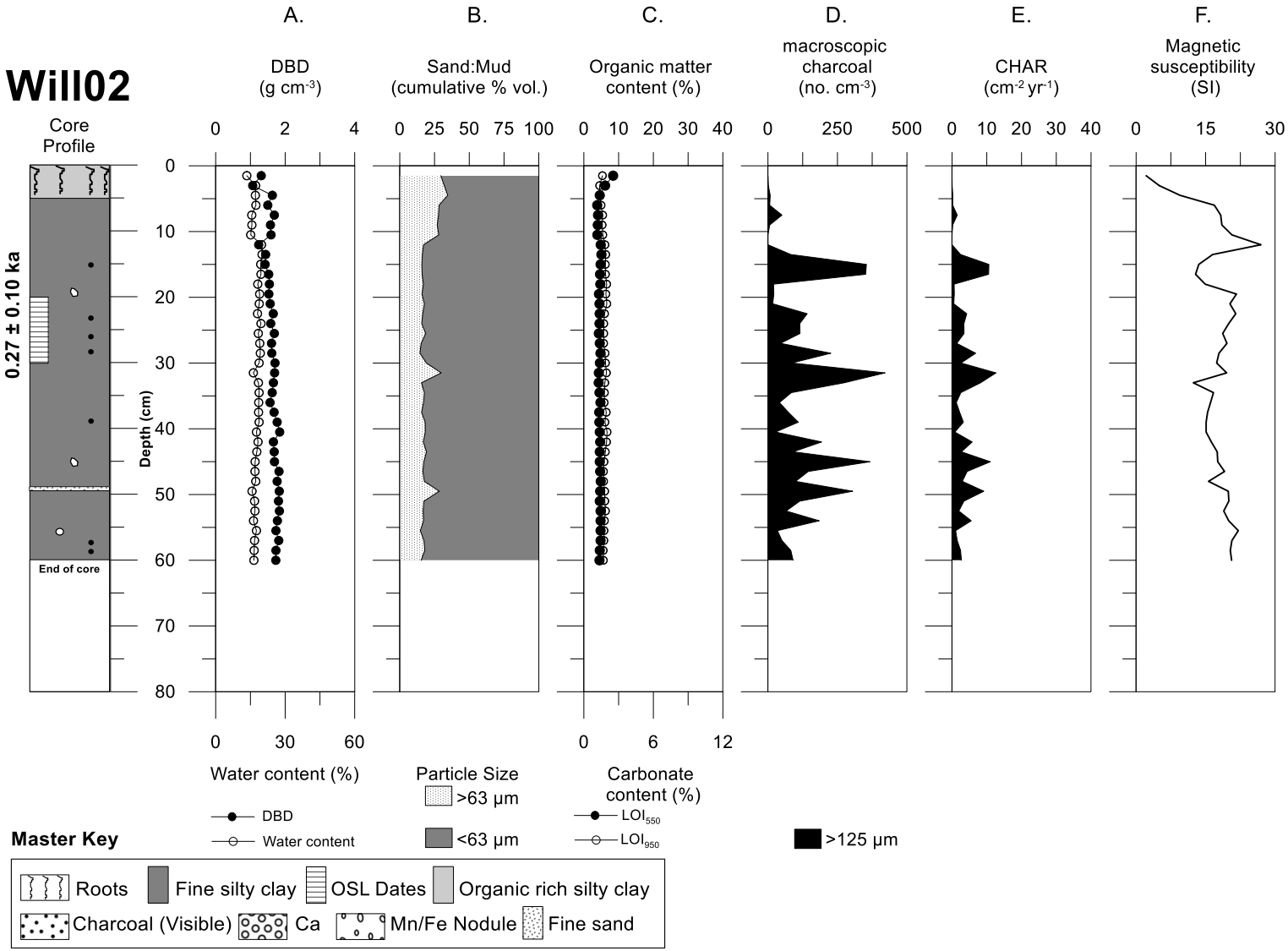

Figure 11: Detailed core description of Will02, including (A) DBD and water content, (B) sand and mud content, (C) LOI_{550} and LOI_{950}, (D) macro-charcoal concentration, (E) charcoal accumulation rate, and (F) magnetic susceptibility.

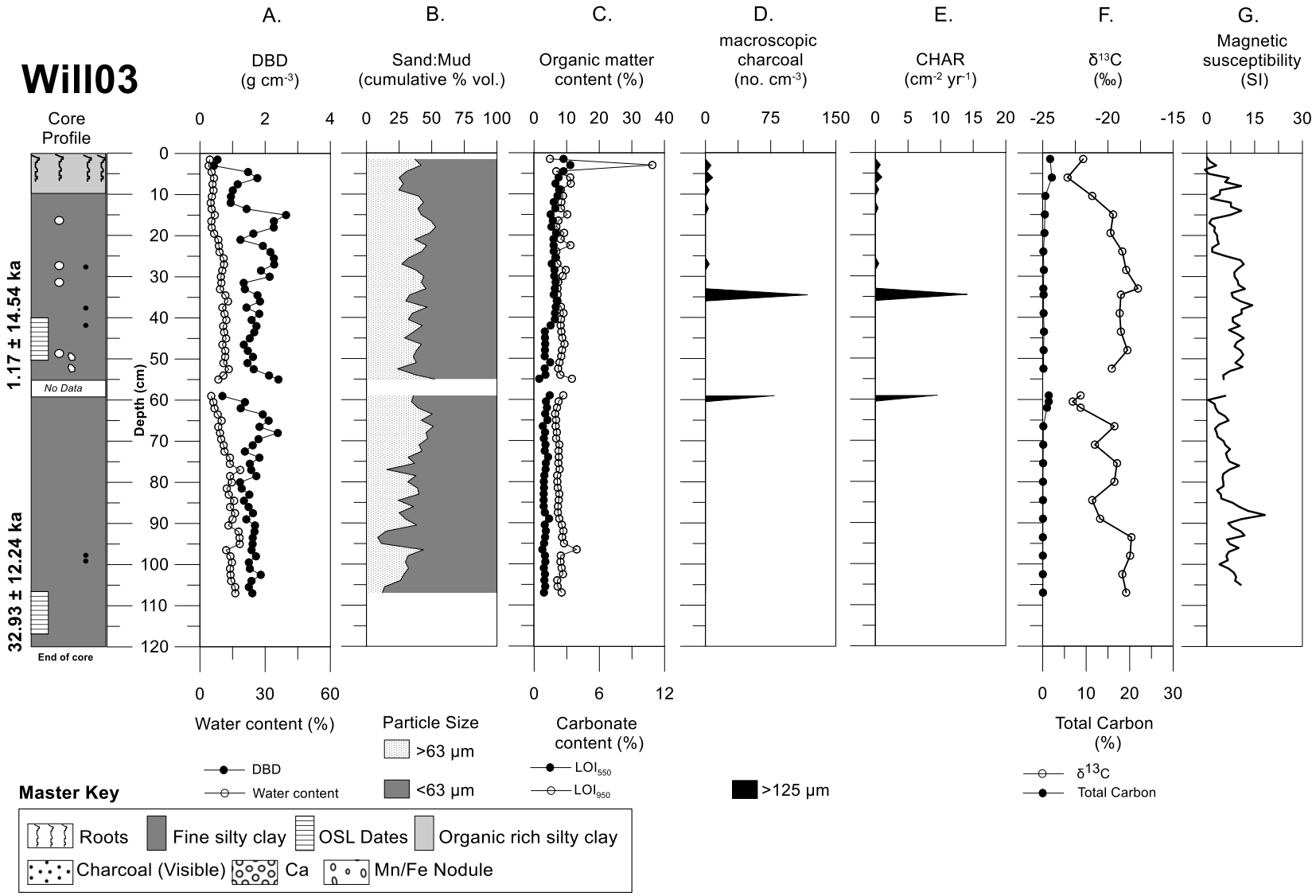

Figure 12: Detailed core description of Will03, including (A) DBD and water content, (B) sand and mud content, (C) LOI_{550} and LOI_{950}, (D) macro-charcoal concentration, (E) charcoal accumulation rate, (F) $\delta^{13}C$ and total carbon, and (G) magnetic susceptibility.

3.5.4 Stable isotopes of carbon

Buck03 $\delta^{13}C$ signatures ranged from -23.7 to -16.7 ‰ in the upper 12 cm of the profile, and then depleted slightly to -22.9 to -20.9 ‰ as total carbon decreased with depth below 15 cm (Figure 10F). In keeping with the organic rich sediment in the upper 15 cm of Buck03, total carbon was highest in this part of the profile and declined to <1 % for the rest of the core.

Will03 $\delta^{13}C$ signatures were more variable throughout the core profile, being close to -22.5 ‰ in the upper 10 cm of the profile and then varying from -19.7 to 17.7 ‰ from 20 to 52.5 cm. A depletion to -22 ‰ was observed from 52.5 to 62 cm where there was also a slight increase in total carbon (up to 1.4%), followed by variations around -20 ‰ in the lower part of the core (Figure 12F).

Overall, there was a significant negative linear relationship between $\delta^{13}C$ and total carbon in Will03 (Figure 13A), but no significant relationship in Buck03 (Figure 13B).

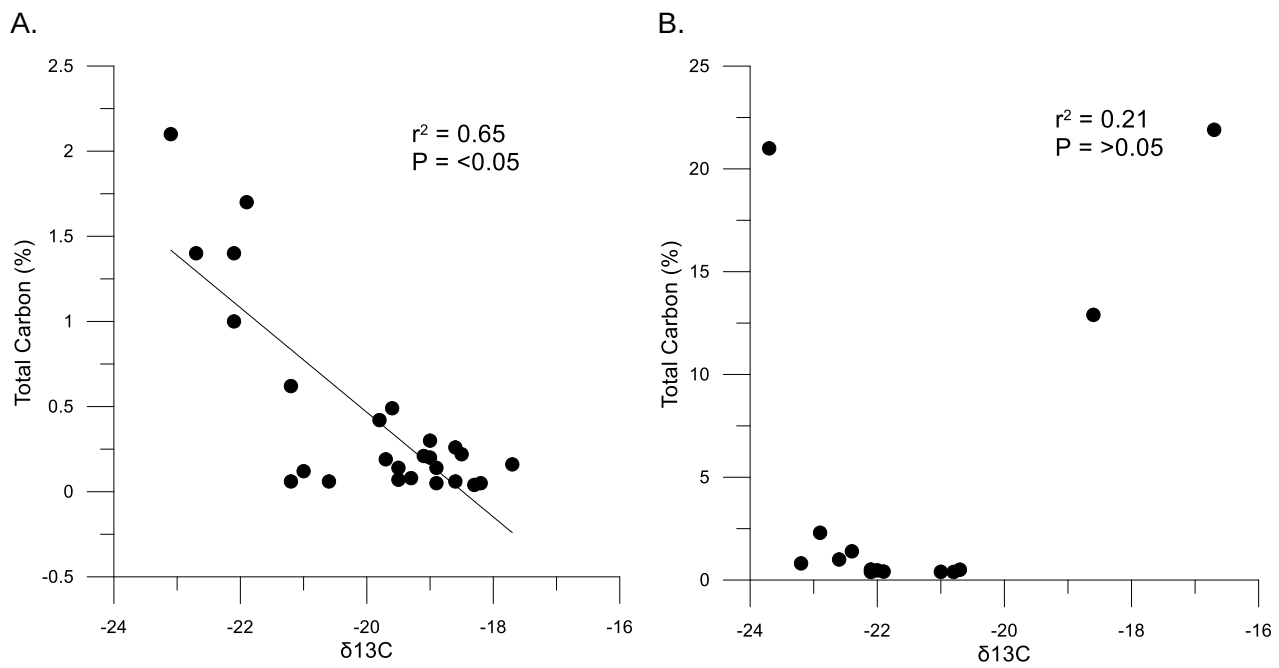

Figure 13: Relationship between $\delta^{13}C$ and total carbon for (A) Will03 and (B) Buck03.

3.4.5 OSL dating and CHAR

The single-grain (SG) OSL age of 0.47 ± 0.11 ka for 20-30 cm sediment in Buck02, is stratigraphically consistent with the 0.90 ± 0.22 ka age for sediment at a depth of 45-55 cm (Table 1 and 2). The OSL ages determined for Buck03 were 1.92 ± 0.31 ka at 20-30 cm and 1.06 ± 0.19 ka at 75-85 cm. However, the Buck03 sample at 75-85 cm only had 14/100 grains accepted, and thus its resulting age estimate is not in stratigraphic agreement with the sample above, and so was not

included in the age-depth model for this core. OSL ages derived from samples with a small number of grains were treated with caution and have only included them as maximum age estimates due to the strong likelihood of partial bleaching.

Therefore, based on the three acceptable OSL ages from the Buckiinguy cores, linear age-depth models provided mean vertical sedimentation rate estimates of 0.05 cm a^{-1} for Buck02 and 0.04 cm a^{-1} for Buck03 (Table 3). These equate to bulk mass accumulation rates of 0.0836 g cm^{-2} a^{-1} for Buck02, and 0.0609 g cm^{-2} a^{-1} for Buck03. CHAR in Buck02 ranged from 0.01 to 0.72 cm^{-2} a^{-1}, with a mean of 0.10 cm^{-2} a^{-1} over the last ~900 years. CHAR in Buck03 ranged from 0.01 to 4.13 cm^{-2} a^{-1}, with a mean of 0.53 cm^{-2} a^{-1} over the last ~2,000 years.

The age of buried sediment in Will02 at a depth of 20-30 cm was 0.27 ± 0.10 ka, while a second sample from 40-50 cm yielded no useable data (Table 1 and 2). The OSL ages determined for Will03 were 1.17 ± 14.54 ka at 40-50 cm and 32.93 ± 12.24 ka at 107-117 cm. However, the Will03 sample at 107-117 cm only had 9/100 grains accepted, and was clearly an order of magnitude different from the other age in this profile, and so for the reasons listed above was deemed to be a maximum age was not included in the age-depth model for this core. Therefore, based on the two acceptable OSL ages from the Willancorah cores, linear age-depth models provided mean vertical sedimentation rate estimates of 0.03 cm a^{-1} for Will02 and 0.04 cm a^{-1} for Will03 (Table 3). These equate to bulk mass accumulation rates of 0.0484 g cm^{-2} a^{-1} for Will02, and 0.0939 g cm^{-2} a^{-1} for Will03. CHAR in Will02 ranged from 0.03 to 12.63 cm^{-2} a^{-1}, with a mean of 3.37 cm^{-2} a^{-1} over the last ~1700 years. CHAR in Will03 ranged from 0.16 to 14.1 cm^{-2} a^{-1}, with a mean of ~0.37cm^{-2} a^{-1} over the last ~1,200 years (see Appendix 3, 4 and 6).

3.5.6 Geochemistry

Magnetic susceptibility is variable but generally increases with depth in both Buck02 and Buck03, but does not appear to align with any changes in sedimentology, organic matter, or macro-charcoal (Figures 9F and 10G). Similarly, magnetic susceptibility is highly variable in both Will02 and Will03 cores, but the peaks and troughs do not appear to align with changes in sedimentology, organic matter or macro-charcoal (Figures 11F and 12G).

ITRAX results (Figure 14) show variable trends throughout all profiles. Fe/Ti has been used as an indicator of smaller grain-size fluctuations from allochthonous material. Fe/Mn is used to assess reducing conditions (redox). Ca/Fe and Ca/Ti ratios suggest pedogenic processes or drier conditions or biogenic production of Ca. Buck03 has a notable correlation between Ca/Ti and charcoal peaks at 15 cm, 20 cm and 35 cm (Figure 14E-K). In Buck02, Fe/Ti and most other ratios

is variable throughout the core (Figure 14). Will02 and Will03 were also highly variable in Ca/Ti and Ca/Fe ratios, but it was difficult to detect any correlations or trends in the geochemical data.

Principle component analysis (PCA) reveals some clustering of detrital and pedogenic elements in Buck02 and Buck03, for example Ti, K, Si, Fe, Rb, Ca (see Appendix 6 and 7). PCA for Will02 also reveals a cluster of detrital elements of Fe, Ti, K, Si, Zn, whereas Will03 PCA has similar spread of detrital elements (see Appendix 8 and 9). However, it is difficult to link PCA from the geochemistry results to variations in macro-charcoal, or macro-charcoal peaks. Stratigraphic profiles of Buck02, and Buck03 with coloured bands representing geochemical groups based on the PCA plots, reveal a combination of detrital and pedogenic elements. Buck02 has a natural break in the geochemical profile at ~15 cm suggesting there are two different geochemical groups, whereas Buck03 has a similar break at ~15 cm. Will02 shows a natural break at ~22 cm in the stratigraphic profile, while Will03 reveals breaks at ~30 and ~55 cm based on the geochemistry. However, the break at ~55 cm is most likely due to contamination where the second part of the core begins. Overall, the results from the PCA and stratigraphic cluster analysis suggest there are natural breaks in the cores geochemically, but they do not reveal any significant trends that correlate with macro-charcoal results.

Table 1: Summary details of OSL and accumulation rates for Buck03, Buck02, Will03 and Will02. Total dose rate, equivalent dose and OSL ages are shown using a minimum age model.

Core	Depth (cm)	Location	Grains accepted	Total grains measured	Equivalent dose (MAM; Gy)	Dose rate (Gy ka^{-1})	Age (ka)
Buck02	20-30	Peripheral swamp	111	500	1.00 ± 0.10	2.116 ± 0.459	0.47 ± 0.11
Buck02	42-52	Peripheral swamp	51	200	1.90 ± 0.20	2.116 ± 0.459	0.90 ± 0.22
Buck03	30-40	Central swamp	189	500	2.10 ± 0.11	1.093 ± 0.157	1.92 ± 0.31
Buck03	75-85	Central swamp	14	100	1.16 ± 0.12	1.093 ± 0.157	1.06 ± 0.19
Will02	20-30	Peripheral swamp	78	500	0.50 ± 0.13	1.835 ± 0.436	0.27 ± 0.10
Will02	40-50	Peripheral swamp	no data	no data	no data	no data	no data
Will03	40-50	Peripheral swamp	17	100	2.10 ± 26.00	1.789 ± 0.680	1.17 ± 14.54
Will03	107-117	Peripheral swamp	9	100	61.00 ± 2.69	1.852 ± 0.682	32.93 ± 12.24

Table 2: Summary of details of the dosimetry data for the selected samples from Buck02, Buck03, Will03 and Will02.

Core	Depth (cm)	Water Content (%)	Beta dose (Gy ka^{-1})	Gamma dose (Gy ka^{-1})	Cosmic dose (Gy ka^{-1})	Internal dose (Gy ka^{-1})	Total dose rate (Gy ka^{-1})
Buck02	20-30	25 ± 5	1.252 ± 0.056	0.678 ± 0.392	0.155 ± 0.015	0.032 ± 0.011	2.116 ± 0.459
Buck02	42-52	25 ± 5	1.252 ± 0.056	0.678 ± 0.392	0.155 ± 0.015	0.032 ± 0.011	2.116 ± 0.459
Buck03	30-40	18 ± 5	0.386 ± 0.143	0.511 ± 0.004	0.163 ± 0.016	0.032 ± 0.011	1.093 ± 0.157
Will02	20-30	20 ± 5	0.966 ± 0.037	0.657 ± 0.390	0.162 ± 0.016	0.032 ± 0.011	1.835 ± 0.436
Will03	40-50	30 ± 5	0.494 ± 0.031	1.117 ± 0.645	0.146 ± 0.015	0.032 ± 0.011	1.789 ± 0.680
Will03	107-117	20 ± 5	0.543 ± 0.031	1.117 ± 0.645	0.159 ± 0.016	0.032 ± 0.011	1.852 ± 0.682

Table 3: Summary of sediment accumulation rate, mean DBD and bulk mass accumulation for Buck02, Buck03 and Will02, Will03.

Core	Location	Mean sedimentation rate (cm a^{-1})	Mean DBD (g cm^{-3})	Bulk mass accumulation rate (g cm^{-2} a^{-1})	Mean CHAR (cm^{-2} a^{-1})
Buck02	Peripheral swamp	0.05	1.55	0.0836	0.09
Buck03	Central swamp	0.04	1.51	0.0609	0.53
Will02	Peripheral swamp	0.03	1.63	0.0484	3.37
Will03	Peripheral swamp	0.04	1.63	0.0939	0.37

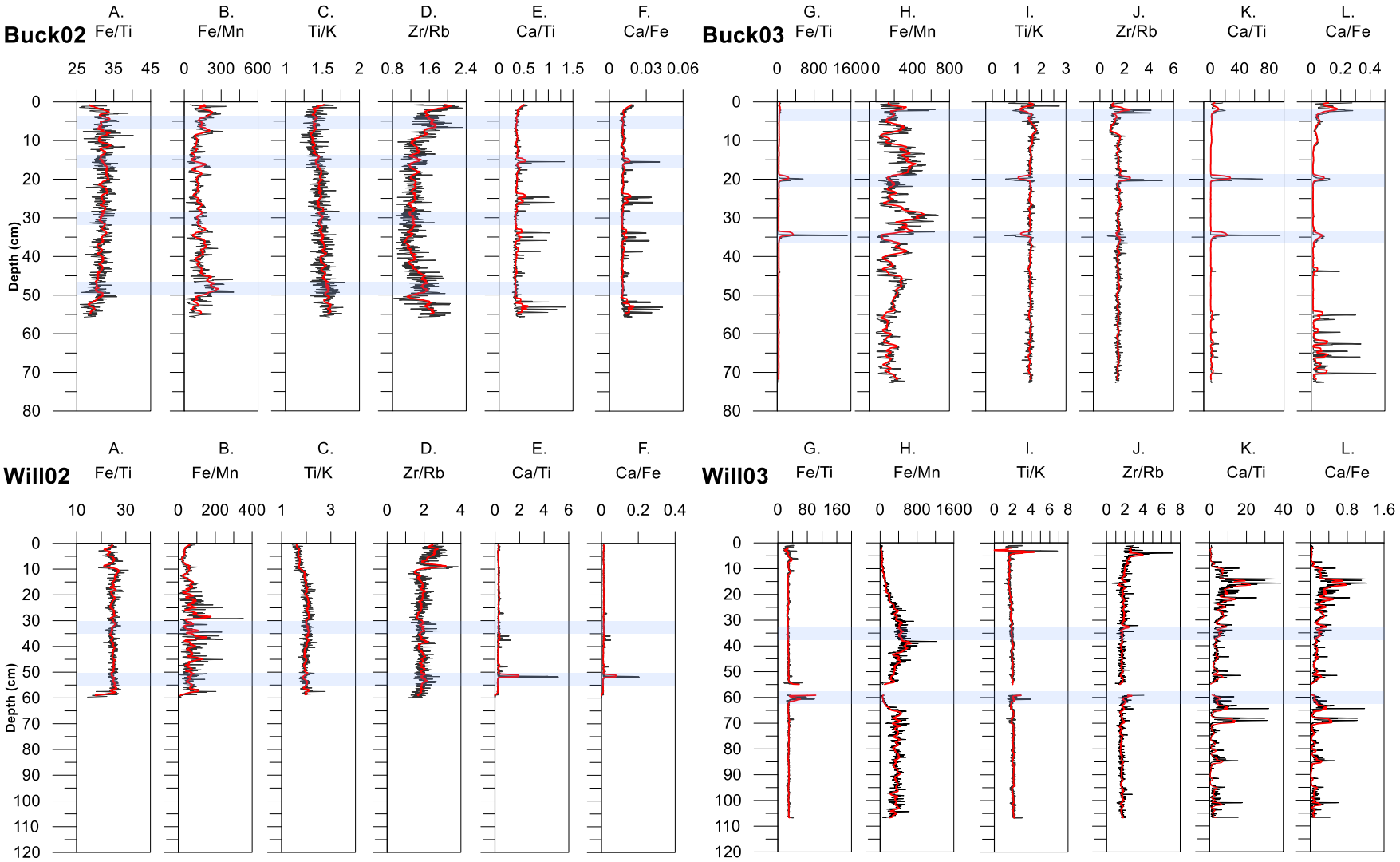

Figure 14: Buck02, Buck03, Will02 and Will03 geochemical ratios from ITRAX including Fe/Ti, Fe/Mn, Ti/K, Zr/Rb, Ca/Fe, Ca/Ti (Redline moving 10-point average and blue shading represent charcoal peaks).

3.6 Discussion

3.6.1 Fluvial background of macro-charcoal

The baseline of fluvial macro-charcoal (16.5 no. cm^{-2}) derived from contemporary sediment deposited in Buckiinguy Swamp over a 9 month period in 2009-2010 shows that charcoal entering the system from upstream is potentially a confounding factor for fire history reconstruction in the Macquarie Marshes and similar floodplain wetlands. Nevertheless, these results were used to isolate the fluvial macro-charcoal signal and to refine the *in-situ* macro-charcoal record for the first time in this type of system. Large variations in the volume of sediment and macro-charcoal deposited downstream and across the floodplain in Buckiinguy Swamp were most likely due to flow attenuation by vegetation and differential patterns of overbank and floodout sedimentation. This is common in low-relief floodplain wetlands where channel breakdown occurs and where in-channel and wetland vegetation blocks flow and distributes water and sediment onto the floodplain (Yonge and Hesse 2009; Ralph and Hesse 2010), affecting sediment and charcoal distribution.

Oris et al. (2014) monitored charcoal accumulation and dispersal in boreal lakes for 3 years (2011 to 2013) and suggested that macro-charcoal could be related to both local and regional fires. The source areas of charcoal and the distance travelled are difficult to disentangle, especially in large catchments where wetlands and floodplain pockets can act as traps filtering charcoal and sediment (Allen et al. 2008). This process was observed in Buckiinguy where the macro-charcoal signal from sites B1-B3 remained low and consistent. However, site B4 yielded a higher charcoal concentration, suggesting that charcoal at this site may have been introduced or reworked by other processes near the outlet of the swamp. Nonetheless, the fluvial macro-charcoal introduced from upstream during the environmental flow in 2009 was able to be used as the background rate of macro-charcoal supply when working with the *in-situ* sedimentary records in the Marshes.

3.6.2 Interpretation of in-situ macro-charcoal profiles

The *in-situ* macro-charcoal profiles from Buckiinguy and Willancorah were highly variable with depth despite the sedimentology being very similar, and there were several inconsistencies between the wetlands, and between cores from the same wetland. Will02 had by far the greatest macro-charcoal concentrations, which was a little surprising given the recent history of fire in Willancorah, which showed that just 6 fires had occurred from 2002-2016. Will03 had two distinct peaks at depth, with very little charcoal in the rest of the profile. This highlights the variability of fire activity and/or charcoal deposition in the wetlands over time, because the long-term macro-charcoal record yields very different results to the short-term satellite record. Conversely, Buck02

and Buck03 had relatively low macro-charcoal concentrations despite Buckiinguy having experienced 33 fires in the period 2002-2016, with several high confidence fire hotspots occurring near the sediment coring sites.

The long-term macro-charcoal record for Buckiinguy Swamp is constrained by OSL dating to the last ~1.9 ka in Buck03, where consistently higher charcoal concentrations exist in the upper 40 cm of the profile and where two CHAR peaks (~5 cm^{-2} a^{-1}) at ~5 cm and ~20 cm occur. Prior to ~1.9 ka, there is little evidence of charcoal preservation. Buck02 has very little macro-charcoal throughout, but the record is constrained to the last ~0.9 ka with four very minor CHAR peaks (<1 cm^{-2} a^{-1}). The variation between these two cores suggests highly variable fire activity in Buckiinguy, with either more frequent, or more intense, fires and/or greater macro-charcoal deposition in the densely vegetated centre of the reed bed (Buck03) as opposed to the margin of the reed bed (Buck02).

The long-term macro-charcoal record in Willancorah Swamp was constrained in Will02 mid-way in the profile to ~0.27 ka, and at Will03 to the last ~1.17 ka. These cores had highly variable charcoal counts with little similarity to the Buckiinguy cores, or each other although they were only taken ~17 m apart at the margin of the swamp. Will02 had large charcoal peaks scattered throughout the core (~5 to 60 cm) with CHAR up to 12 cm^{-2} a^{1} suggesting a greater frequency or intensity of fire over the past ~250 years. Will03 had with two large CHAR peaks at ~35 cm (~15 cm^{-2} a^{-1}) and 59-60.5 cm (~10 cm^{-2} a^{-1}) suggesting isolated or irregular fire activity around ~1700 years ago.

A much older OSL age obtained at the base of Will03 is interpreted as age over-estimation due to the very small population of accepted grains (n=9), and therefore was not used to calculate CHAR. This anomalous age could be due to partial bleaching during sediment transport and deposition, which prevents the complete resetting of the luminescence signal and is common in fluvial systems (Madsen and Murray 2009; Sloss et al. 2013). The marshes have formed over the last ~6000 to 7000 years (Yonge and Hesse 2009), so the ~33 ka age at the base of Will03 is a maximum age for the marshes and could potentially represent the age for the underlying palaeo floodplain.

Any attempt to reconstruct fire regimes in large wetlands and/or catchments is difficult due to the issues associated with using macro-charcoal as an indicator of local fire history. Most palaeofire studies examine and interpret macro-charcoal from one or two sediment cores at high resolution (e.g. Black et al. 2008; Fletcher et al. 2014; Stahle et al. 2016). Preferably, this is done in small, closed systems due to their propensity to accumulate and preserve charcoal and sediment

over time. There have been limited number studies trying to cross-correlate charcoal records in an attempt see if similarities or reproducibility of down-core patterns of charcoal concentration is possible (Allen et al. 2008). This study attempted to correlate charcoal records from two key wetlands to see if it is feasible to examine and link charcoal signals is in large, dynamic wetland system, but the results suggest that charcoal deposition and fire regimes are highly variable in space and time. Although both Buckiinguy and Willancorah are known hotspots of fire activity, the macro-charcoal records must be treated with caution, thus, the macro-charcoal profile cannot be interpreted with confidence as a record of past fire activity.

Interpreting local fire history relies on the assumption of primary charcoal being rapidly deposited and buried during and immediately after a fire event; conversely, any charcoal incorporated later is regarded as secondary or from non-fire years (Whitlock and Larsen 2001). It is plausible that secondary charcoal may have contributed to peaks in the Marshes during non-fire years because of surface runoff, sediment mixing or bioturbation throughout the profiles, or from charcoal inputs from another source zone within and outside the catchment (Clark and Royall 1996; Whitlock and Millspaugh 1996; Whitlock et al. 2003). For example, Buckiinguy floodplain may have burned numerous times over the last 900 years but other charcoal has been transported and deposited into the swamp, leaving a trace of higher concentrations of charcoal. Willancorah Swamp too is likely to act as a sink for charcoal from upstream. Additionally, taphonomic processes, including bioturbation in the upper sections of the profiles, could have affected charcoal preservation, perhaps due to termites over the long-term or livestock in paddocks on the floodplain more recently. For example, the physical properties of Vertosols soils (Isbell 1996; Yonge and Hesse 2009), could also influence the preservation of charcoal (e.g. self-mulching), where the physical shrink-swell properties of clay soils in response to sporadic wetting and drying cycles could impact the count and distribution of charcoal in the profile. Furthermore, livestock have been known to spend a significant amount of time in and around wetlands where they trample and churn the topsoil (DECCW 2010; Berney 2011; Whalley et al. 2011). This could be factor in the Marshes, as both swamps are located on private land and prior to sampling both sites had some evidence of cattle grazing activity.

Altogether, the catchment conditions, geomorphic setting, climate, ignition sources, and readily burnable biomass can all effect the transport, deposition and taphonomy of charcoal in a sediment profile (Pisaric 2002; Tinner et al. 2006; Conedera et al. 2009). Theoretical models of charcoal dispersal predict that larger particles of charcoal should decrease with distance from the burn area (Clark 1988a; Higuera et al. 2007). Nevertheless, it remains a possibility that in a large catchment entering a semi-arid climate zone such as the Macquarie, macro-charcoal distribution

may occur sporadically during large floods or rainfall events. However there have only been a limited number of empirical studies validating this, through either natural or prescribed burns using traps within proximity of the burn (e.g. <200 m) to collect charcoal and track dispersal patterns (Clark et al. 1998; Ohlson and Tryterud 2000; Gardner and Whitlock 2001; Lynch et al. 2004). Although, it might be reasonable to infer the charcoal record for the Buckiinguy and Willancorah Swamp within a certain distance (e.g. 200 m) and assigning it as a local fire is not enough using the models above. Especially in this case, due to the large catchment area, uncertainty and potential for long-distance dispersal of charcoal within and outside the catchment. Therefore, further research is warranted and required to explain these macro-charcoal patterns.

3.6.3 Interpretation of $\delta^{13}C$ signatures

Carbon stable isotope analysis can help disentangle vegetation shifts in the environment over time as well as the interpretation of past environmental conditions (Ehleringer et al. 2000; Staddon 2004). The discrimination of $^{13}CO_2$ by plants through diffusional and biochemical reactions from carbon fixing enzymes can help assist in separating different types of photosynthetic groups (Pack et al. 2003). C3 plants tend to have values ranging from -40 to -20 ‰ typically constituting woody species, whereas C4 plants consist of mostly grasses with values of -17 to -9 ‰ (Leng and Marshall 2004; Staddon 2004). The C4 plant water couch (*Paspalum distichum*) has a typical $\delta^{13}C$ value of -18.7 ‰, while the C3 plant common reed (*Phragmites australis*) has typical values of -28.2 to -27.6 ‰ (Kelleway et al. 2010ap. 90; Whitaker et al. 2015) (see Appendix 5). In this study, the $\delta^{13}C$ profile from Buck03 suggests a C4 signature in the upper 10 cm, while below 10.5 cm, $\delta^{13}C$ values tend to resemble a C3 signature. In contrast, Will03 revealed a possible mixture of C3 and C4 vegetation throughout the core since the values remain close to -20 ‰. Although there appears to be a shift towards C3 species at 59-62 cm in Will03, this could either be contamination caused by the coring process or be related to other factors affecting the $\delta^{13}C$ values. This includes the influence of bacteria, algae, sugars or starch in leaves can affect the *in-situ* source values of $\delta^{13}C$, as well as possible isotope fractionation, thus making it difficult to specifically designate whether C3 or C4 vegetation was prevalent a given time using $\delta^{13}C$ data alone (Pack et al. 2003; Lamb et al. 2006; Bowling et al. 2008).

Total carbon decreases in the cores and had a negative relationship with $\delta^{13}C$ in Buck03, suggesting that the storage of carbon in the wetlands is minimal and is restricted to the upper organic rich parts of the cores, which was also observed in a previous study of carbon in the Macquarie Marshes (Whitaker et al. 2015). Overall, interpreting changes in $\delta^{13}C$ and total carbon

results and attempting to relate these to vegetation succession and/or fires is not feasible in this case.

3.6.4 Interpretation of geochemistry

Magnetic susceptibility results from Buckiinguy and Willancorah were inconsistent and did not show any correlations with macro-charcoal peaks. Magnetic susceptibility has been used as a proxy to help distinguish between sources of magnetically transported allogenic clastic minerals in lakes (Dearing and Flower 1982; Rummery 1983; Thompson and Oldfield 1986; Dearing 1999). Fire can remove surface coverage of vegetation and strip the ground clear leaving it susceptible to erosional processes (Thompson and Oldfield 1986). Magnetic susceptibility coupled with charcoal records could possibly help in an attempt to discriminate the allochthonous input of minerogenic material from fire events (Millspaugh and Whitlock 1995; Long et al. 1998). Millspaugh and Whitlock (1995) and Long et al. (1998) attempted to use magnetic susceptibility and charcoal results to assess the role of fires as triggers for erosional events. However only some charcoal peaks were correlated with magnetic susceptibility suggesting fire is not the only disturbance agent to instigate erosional processes. Magnetic susceptibility in a system like the Macquarie Marshes could vary due to sediment particle size, pedogenic nodules of iron or manganese, or more complex processes related to the input of sediment and river discharge that govern the system.

The elemental ratios from ITRAX scanning from Buckiinguy and Willancorah were highly variable and did not readily correlate to other parameters, which did little to disentangle detrital inputs from *in situ* formation (i.e. pedogenic processes). In other systems, ratios of geochemically stable elements have been used to track chemical or physical weathering in catchments and as indicators of detrital inputs (Davies et al. 2015). Titanium (Ti) is used more readily then other elements (e.g. iron, Fe) as a reliable indicator of detrital input as Fe and other elements can be affected by reduction and oxidation processes (Metcalfe et al. 2010). Variations in grain size combined with geochemical data (e.g. Fe/Ti) of allochthonous material in lake sediment has been used to infer different types of energy conditions at the time of deposition and the nature of the derived material (Kylander et al. 2011). Buck03 is the only core that has two distinct CHAR peaks that correlate with ITRAX data for Fe/Ti coinciding with Fe-rich clastic material suggesting detrital input or a fire exposing bare soil. Haberzettl et al. (2007) used Ca/Ti ratios to infer hydrological variability where high values indicate drier conditions and low values indicate wetter conditions. Buck03 has increases in Ca/Ti at ~20 cm and ~35 cm that seem to correspond with an increase in charcoal concentration, which may be related to drier conditions and coincides with higher sand content suggesting the possibility of increased fluvial deposition of charcoal and sediment

altogether. Will02 at ~52 cm also has a spike in Ca/Ti, however, this is not seen in all cores, since Will03 has no Ca/Ti peak at 35 cm corresponding with a charcoal peak, nor does Buck02 have matching peaks (except for ~15cm). Overall, both PCA and stratigraphic plot analysis of cores from Buckiinguy and Willancorah both showed highly variable results with no significant standout trends or correlation between charcoal records.

3.6.5 Fire history and fire management in floodplain wetlands

Clearly, floodplain wetlands such as Buckiinguy and Willancorah Swamp in the Macquarie Marshes have complex and highly variable sediment, charcoal, isotope and geochemical records that defy simple interpretations and straightforward fire history reconstructions. The most reliable indicator of recent fires is Sentinel Hotspot data, which, when combined with on-ground fire assessment and monitoring, could be a powerful tool for wetland and water managers who need to understand fire activity, patterns and regimes in floodplain wetlands. Assessing the long-term fire records in floodplain wetlands using charcoal as a proxy to inform wetland management and conservation practices would be ideal, but more research is required to guarantee a reliable outcome.

Wetlands are complex systems and their resilience under land use, water and climate change scenarios will be tested when additional pressures come in the future. Floodplain wetlands are already difficult to manage due to the numerous environmental, social and economic factors that are inherent to these unique environments. In Australia, many of our wetlands have deteriorated due to water regulation and intensification of agriculture (Kingsford 2000; Finlayson et al. 2013), but little is known about the role of managed fires in helping or harming floodplain wetlands. Understanding past changes and variability in changing fire patterns can be incorporated into future management plans. For example, the CSIRO (2008) report for the Murray-Darling Basin identified that reduced rainfall, water availability (~12 % across the Basin, Figure 15), flood frequency and flood volume (Figure 16) are expected in a drier climate by 2030, with impacts on both wetland flora and fauna. It is also likely that the Murray-Darling Basin will suffer from more intense and prolonged droughts (Figure 17). Floodplain wetlands such as the Macquarie Marshes might be hardest hit by reduced water availability and enhanced droughts, because they are dependent on water from upstream to support critical habitats for flood-reliant and flood-tolerant biota (Ralph et al. 2016). When core floodplain wetland areas dry out they also become more susceptible to fire. The increased likelihood of fire activity when coupled with drier conditions and water resource competition could place severe or catastrophic pressure on wetland communities (OEH 2013). In particular, for the

Macquarie Marshes it has been identified that water (including environmental flows) and fire impacts are of growing concern and greater attention is needed from a management perspective (Berney and Hosking 2016).

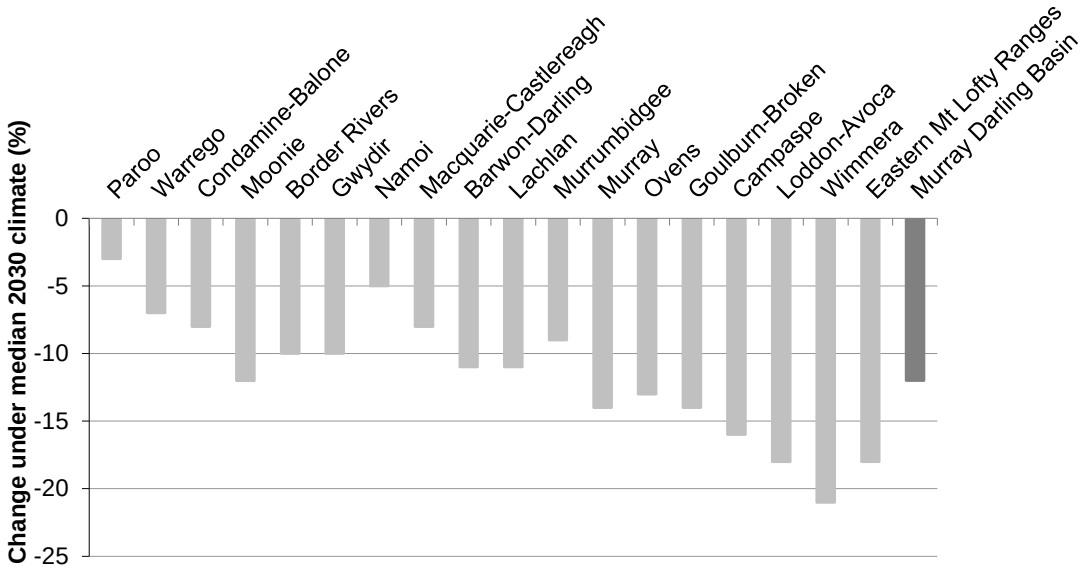

Figure 15: Surface water variability projections for 2030 median climate projection from different subregions in the Murray-Darling Basin (CSIRO 2008).

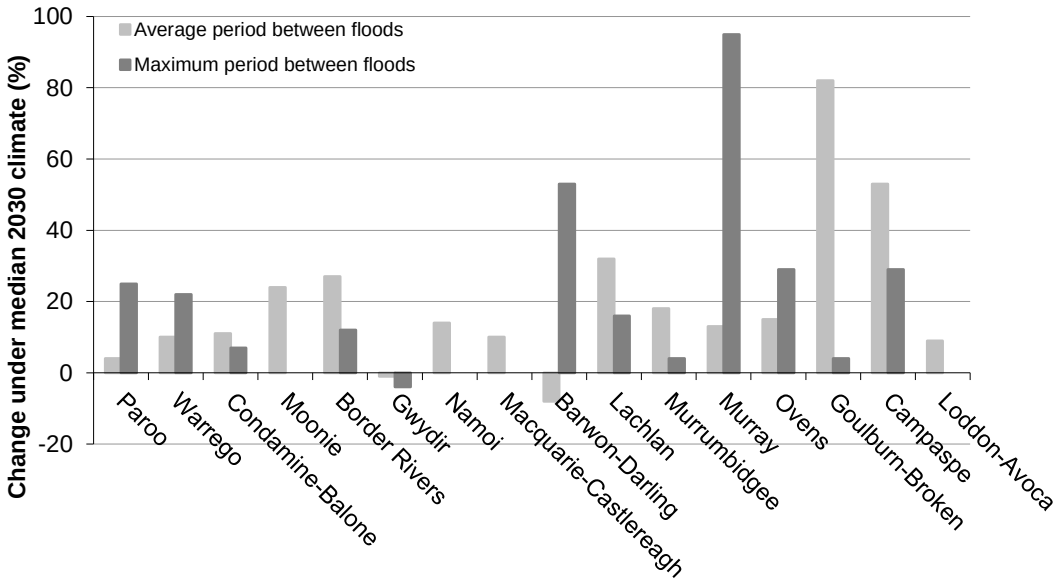

Figure 16: The average and maximum periods between floods under a median 2030 climate for floodplain wetlands across the MDB including other environmental indicators (CSIRO 2008).

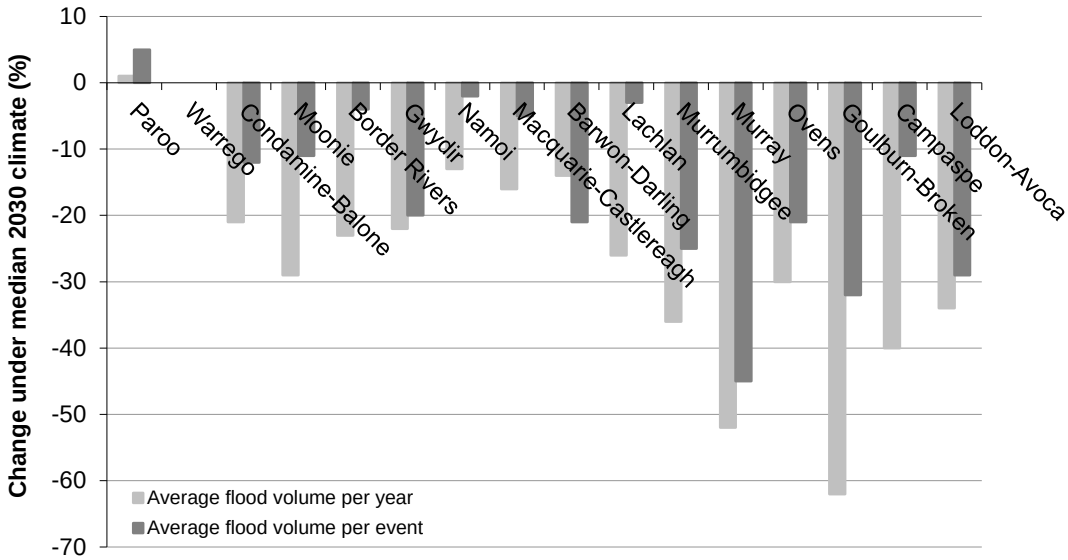

Figure 17: Significant decline in the reduction of flood water volume per year and per event under the 2030 median climate projection (CSIRO 2008).

Understanding the geomorphic factors that distribute water within floodplain wetlands is critical for any future management regarding fire activity. The numerous low-sinuosity distributary channels throughout the Macquarie Marshes that feed water into perennial and ephemeral wetlands are extremely important geomorphic features (Yonge and Hesse 2009; Ralph and Hesse 2010). The complex nature of surface drainage lines, low levees, flood retention zones, floodouts, and gilgai (i.e. depressions due to clay shrinking and swelling properties due to water) are just some of the geomorphic units (Yonge and Hesse 2009). They are a function of channel and floodplain erosion, sedimentation and depositional process that can control the direction and redistribution of the amount of overbank flooding across the floodplain and in the system as well (Ralph et al. 2011). Overbank flooding is a critical driver of wetland vegetation and habitat for various aquatic and terrestrial species, but with the lingering pressure of reduced rainfall, greater evapotranspiration, variability in flood magnitude and size it is likely the current contemporary channels in the marshes will change (Ralph et al. 2011; Rogers and Ralph 2011) The loss of channel-floodplain connectivity due to a reduction in medium to large floods due to hydrological variability surface water availability under changing climate, could have a greater impact on floodplain vegetation and extant, extensive drying of vegetation can exacerbate the risk of a major fires across the system due to reduced surface water distribution due to the current contemporary (but not static) geomorphic state the system is currently in.

Vegetation provides the necessary fuel for fire to burn in any environment where suitable ignition conditions occur. Key wetland communities such as river red gum forests are susceptible to

fire but have little resilience to intense fires, whereas reed beds are susceptible to fire activity but bounce back if their roots are inundated and their rhizomes do not get destroyed. However large and devastating reed bed fires can occur if fuel loads are excessively high when above-average rainfall leads to prolific growth followed by intense drying (DECCW 2010; OEH 2012). In the past common reed was burned to encourage regrowth for grazing purposes, and these plants could tolerate low intensity fires, but under drier conditions dense reeds are prone to more intense fires (OEH 2012). Vegetation communities provide critical and significant habitats for woodland birds, migratory birds and support breeding events (Kingsford and Auld 2005; Bowen and Simpson 2010; Rogers and Ralph 2011; OEH 2012). However, fire poses a significant risk to the survival of these vegetation communities if it occurs with decreases in water availability and channel-floodplain (dis)connectivity, coupled with the inability to maintain a seedbank and to maintain their reproductive capability under drier future climates (Rogers and Ralph 2011).

Ultimately, fire management is a difficult and challenging task in any setting, but especially in wetlands in drylands in Australia. Fire-climate-vegetation-hydrology interactions are complex and require a holistic understanding and appropriate management response. Climate change will only exacerbate fire weather conditions in many regions through changing and altering vegetation composition, structure and integrity of species (Lucas et al. 2007; Bradstock et al. 2014). Ecological stress, changing hydrological regimes, drought and wetland management practices in the Macquarie Marshes have been observed to change over the past decades (Kingsford 2000; Bowen and Simpson 2010; OEH 2012). Although the main threat to the Marshes is alteration of the flow and inundation regime, threats to biodiversity values in important wetland areas also come through lightning strikes leading to intense wildfires (NPWS 1999; OEH 2012; Berney and Hosking 2016). Assessing the longer-term history of fire and prioritising sites based on a sufficient reliable palaeoenvironmental records could help guide future wetland management if: 1) the sites are stable and have been prone to fire in the past (based off contemporary records), 2) there is potential for charcoal preservation and biological remains and their disturbance is minimal, and 3) potential impacts to water and ecological flora and fauna are understood. Understanding the historical fire regime is important over recent decades and past centuries, but using sediment profiles in morphodynamic, semi-arid floodplain wetlands is unlikely to yield suitably accurate and reproducible information at this time.

3.7 Conclusion

This novel study used macro-charcoal and other environmental proxies to investigate fire activity in two key ecological assets, Buckiinguy and Willancorah Swamp, in the Macquarie Marshes. The application of macro-charcoal other environmental proxy data as an indicator of local

fire history is inherently difficult in large floodplain wetland systems due to variations in charcoal sources, deposition, fluvial supply rates, and taphononmy. Despite the removal of the fluvial background, these results cannot simply be used to reconstruct local fire regimes. Further research is required spatially and temporally to extend the history of fire from these two sites in the Macquarie Marshes to support the observations presented in this study.

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3.9 References

See combined reference list at the end of the thesis

Chapter 4 Conclusion

4.0 Summary of major findings

The purpose of this study was to address the research question: *"Can macro-charcoal combined with other environmental proxies be a reliable indicator of past fire activity in the Macquarie Marshes?"* Clearly, floodplain wetlands in the Macquarie Marshes have complex and highly variable sediment, charcoal, isotope and geochemical records that defy simple interpretations and straightforward fire history reconstructions.

The key findings from this study relate directly to the aims from Chapter 1:

1. *Determine whether there an interpretable fire history in the sediment profiles of Buckiinguy and Willancorah Swamps based on analysis of macro-charcoal in sediment.*

This study identified the short-term fire history in the Marshes using satellite data from Geoscience Australia (Sentinel Hotspot). The fire ignition points revealed Buckiinguy has possibly been susceptible to greater fire activity (33 ignition points) compared to Willancorah (6 ignition points) from 2002-2016. The long-term sediment record goes back to ~1.9 ka in Buckiinguy and to ~1.7 ka in Willancorah, however the macro-charcoal record from these wetlands were highly variable with depth despite the sedimentology being very similar, and there were inconsistencies between the wetlands, and even between cores from the same wetland. Therefore, the long-term evidence of fire history is not well-constrained, and further research is required to resolve issues with macro-charcoal variation, sources and preservation in the wetlands.

2. *Measure the type and amount of fluvial charcoal entering the system from upstream to distinguish a background of macro-charcoal supply from in situ macro-charcoal in sediment cores linked to wetland fire history.*

Fluvial macro-charcoal extracted from modern sediments deposited on mats provided a mean baseline of 13.5 ± 3.2 no. cm^{-3} which was then subtracted from the down-core macro-charcoal records. Unfortunately, this data came only from Buckiinguy, and therefore the supply of charcoal to Willancorah had to be assumed to be equivalent. The derived *in-situ* macro-charcoal records from cores in both wetlands were highly variable, as described above, and so further research is required to fully understand the fluvial inputs of charcoal in this large, dynamic wetland system.

3. *Examine whether macro-charcoal, combined with other environmental proxies, can provide evidence of a fire regime in the wetlands, which may then help guide future fire management .*

A combination of macro-charcoal records and other environmental proxies could be beneficial for management practices if the environmental setting is: (1) stable and prone to fire, (2) the preservation potential for charcoal and other biological material is adequate, and (3) ecosystem impacts of flora and fauna are understood. Unfortunately, these conditions are difficult to satisfy in wetlands of the Macquarie Marshes.

4.1 Directions for future research and recommendations

This study leads to several potential pathways for future research in floodplain wetlands:

1. Enhancing the reproducibility of the current charcoal record by taking additional and deeper sediment cores from the wetlands this would allow greater spatial and temporal coverage and sites for cross-comparison. Specifically, the northern Macquarie Marshes could be investigated, which have been shown to be a hotspot of recent fire activity.
2. OSL dating can provide rigorous age results, however it is labour intensive and expensive, and any work future sediment cores will require caution when selecting sites and samples to use for OSL. Additional OSL ages would provide a higher temporal resolution which will be beneficial for interpreting the timing of fire events and other environmental changes.
3. The application of other environmental proxies (i.e. diatoms, pollen, dendrochronology, micro-charcoal, etc.) could assist with further assessment and interpretation of fire history in floodplain wetlands, while also enhancing the long-term record. However, the potential for preservation in these environments would need to be considered beforehand.
4. This research has provided a first attempt to disentangle the history of charcoal deposition and fire within a unique and dynamic floodplain wetland system. It has highlighted the problems and prospects that possible future research may address in wetlands in drylands.

In summary, this study has provided a novel insight into the possibility of reconstructing a fire history in a large, open-system floodplain wetland in semi-arid eastern Australia. The findings from the study have demonstrated that pursing fire histories in open-systems is challenging, and that additional work is needed to reconstruct a sufficient and reliable palaeofire and palaeoenvironmental record from the Macquarie Marshes. If a longer-term record is producible, reliable and accurate, then it may be useful guide for wetland management in the future.

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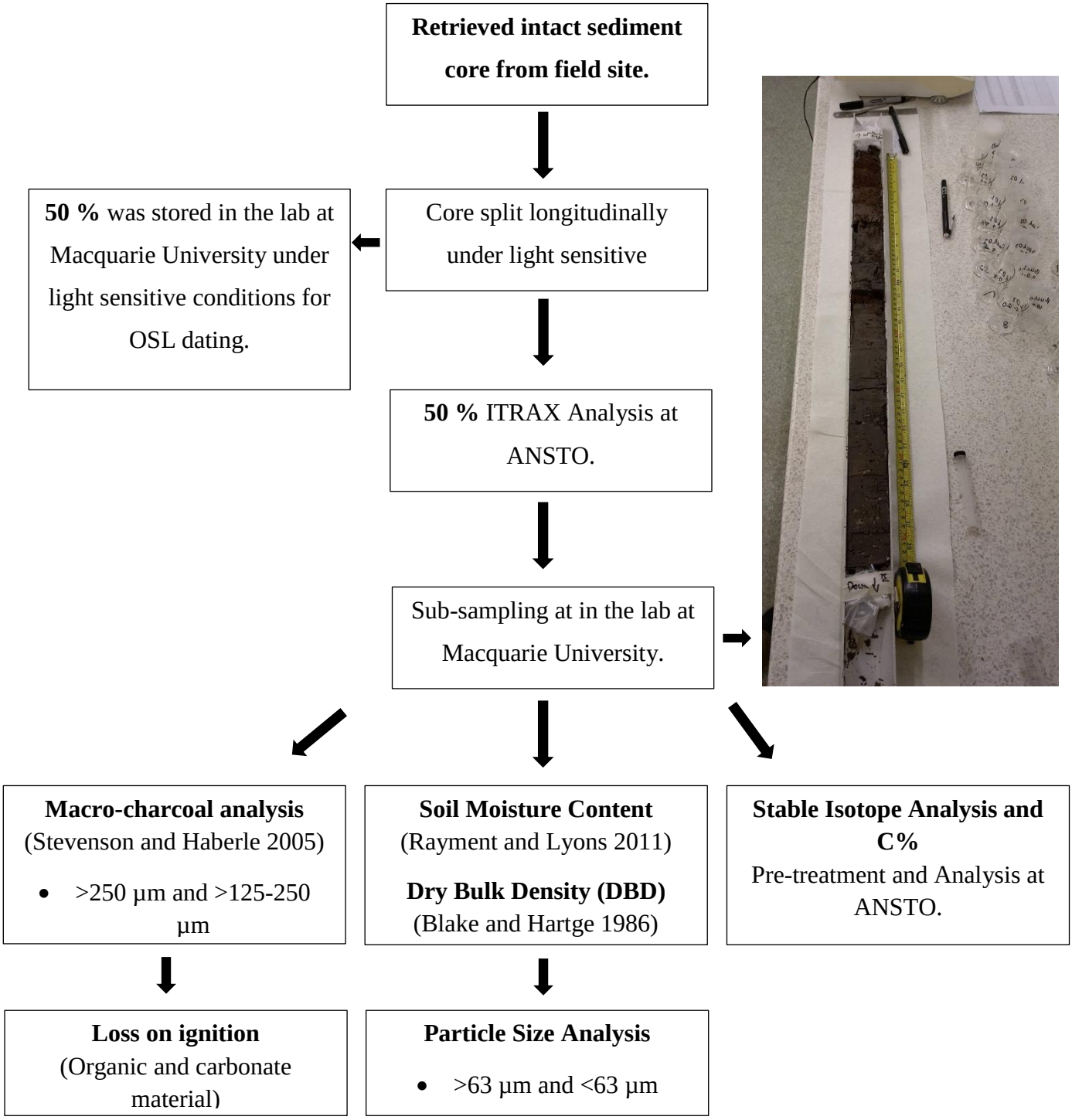
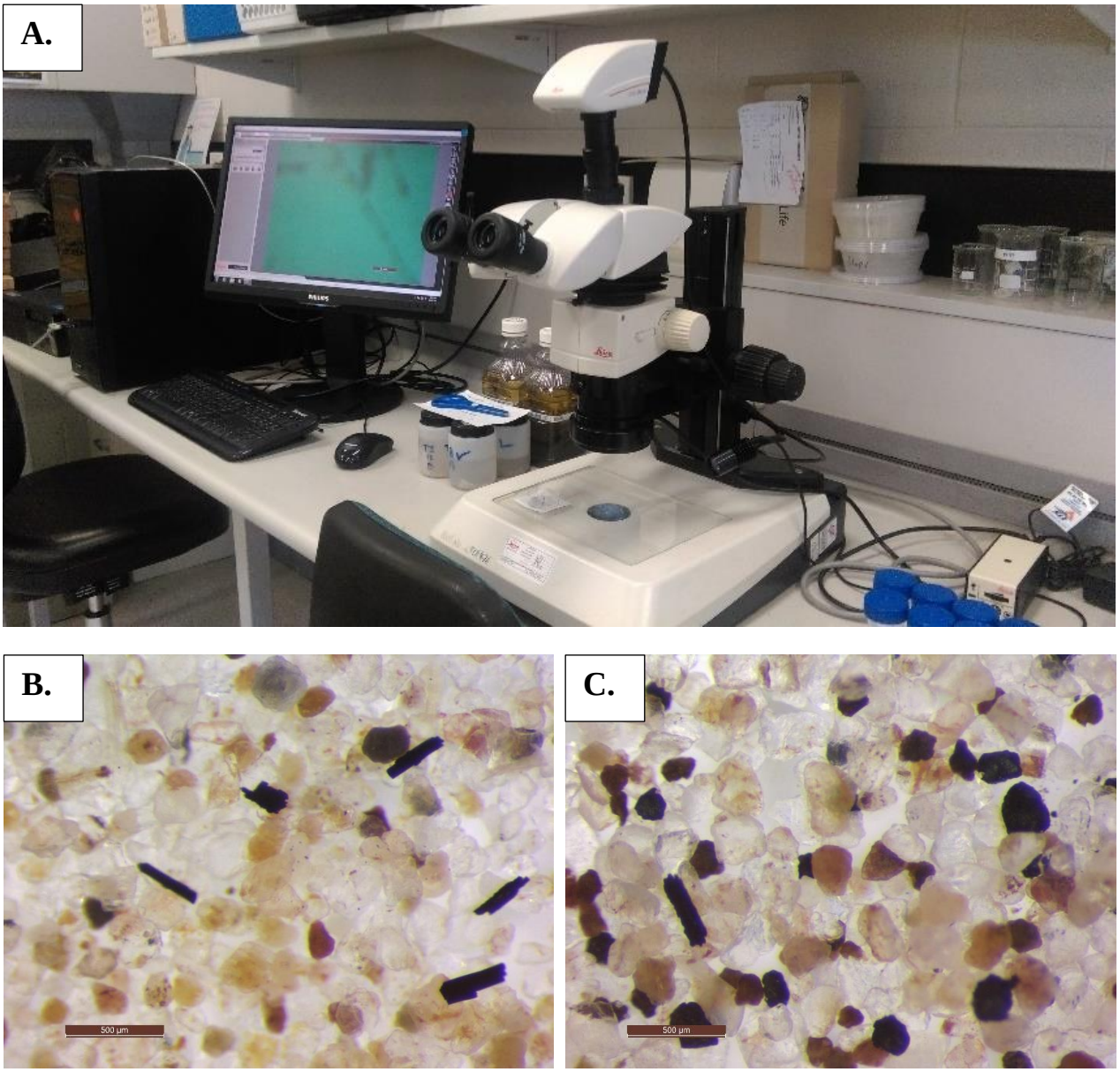
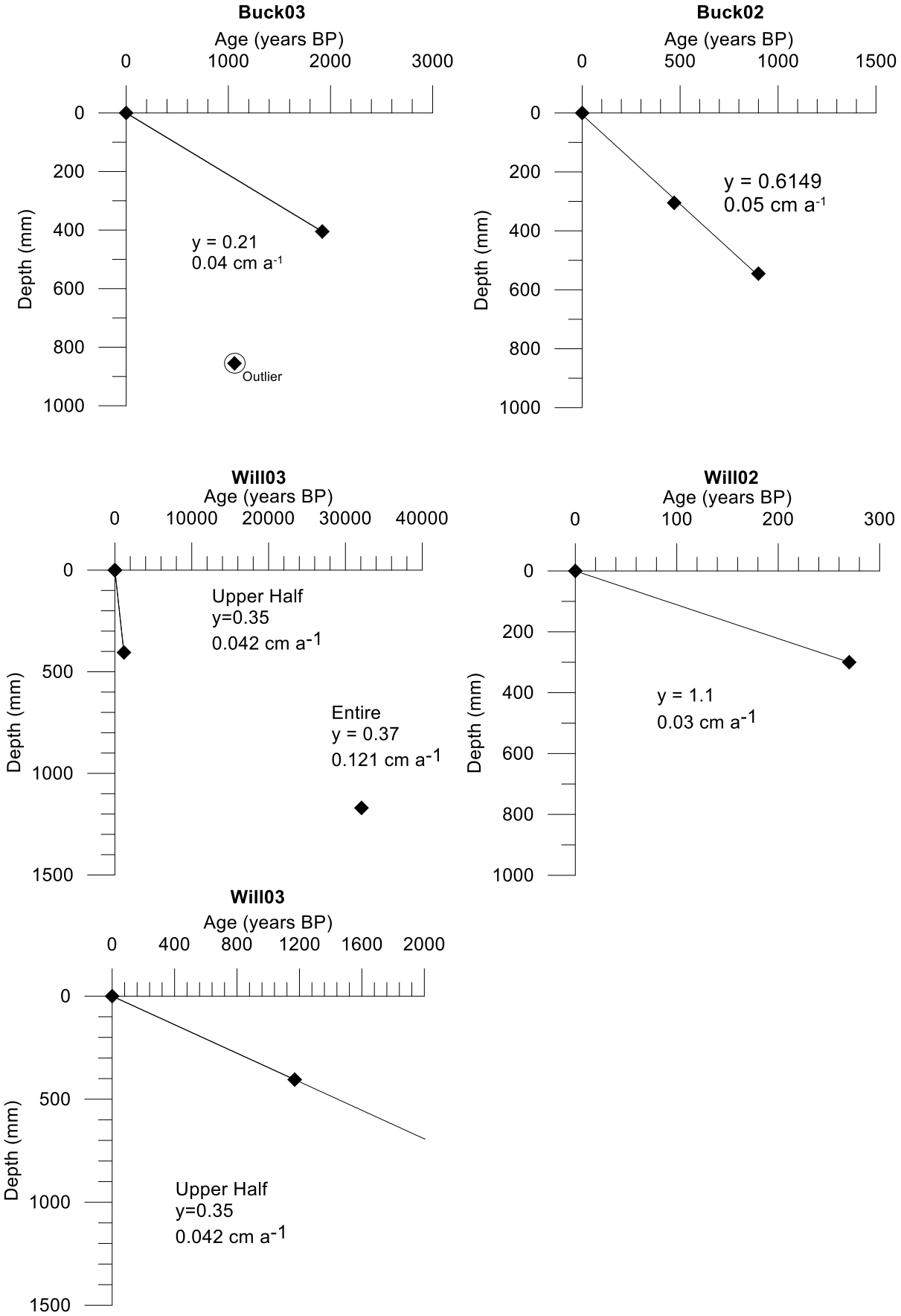
Chapter 6 Appendices



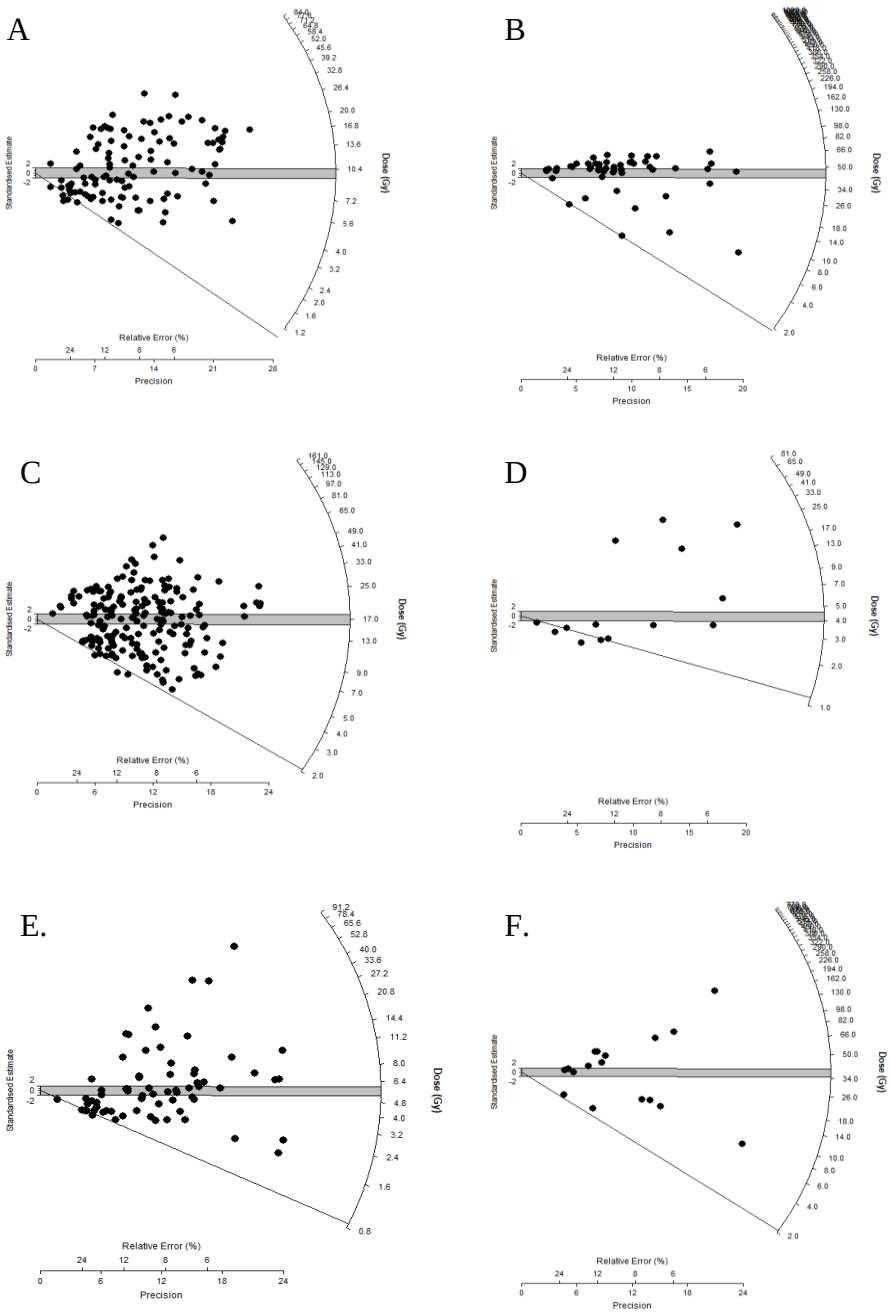
Appendix 1: Flow chart of the sample processing procedure for intact sediment cores collected from Buckiinguy and Willancorah Swamp in the Macquarie Marshes.

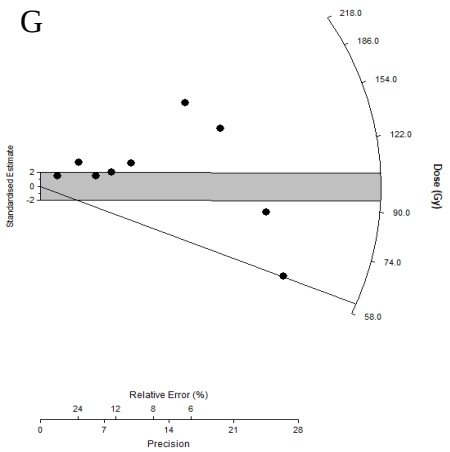


Appendix 2: (A) Microscope analysis at OEH Laboratory Sydney, NSW. Images obtained throughout the Macro-charcoal analysis (500 µm scale bar) from both Buckiinguy and Willancorah Swamp cores including, (B) >125 µm fraction Buck03 at 31.5 cm depth, and (C) >125 µm fraction Will02 at 13.5 cm depth.



Appendix 3: Age-depth Models for Buck02, Buck03 and Will02, Will03.

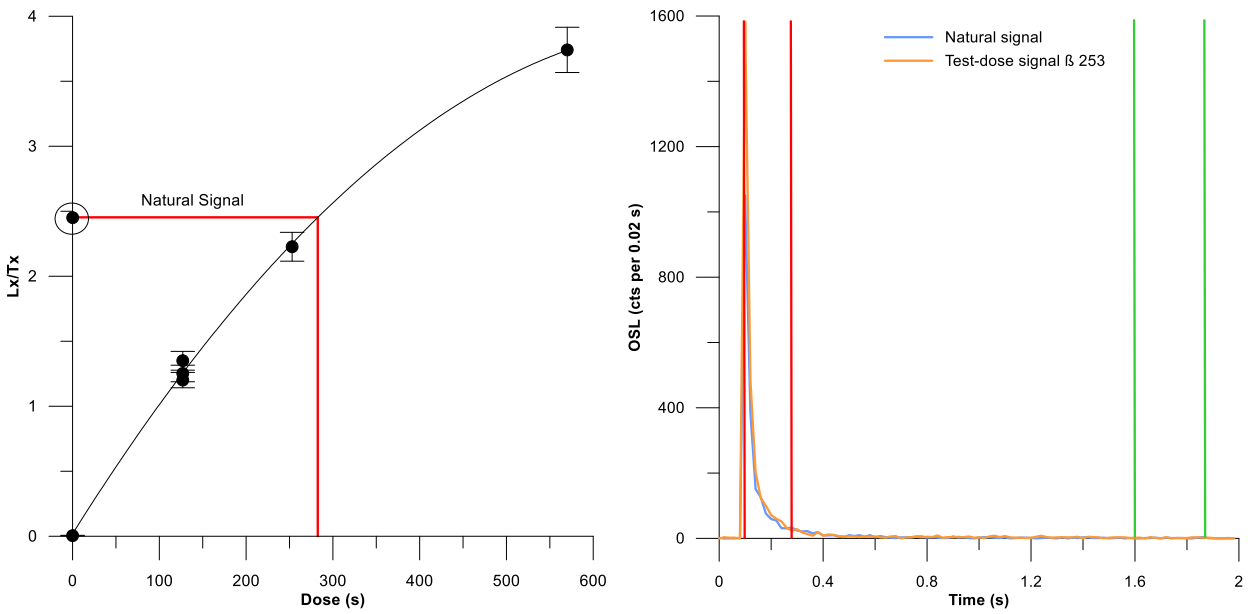




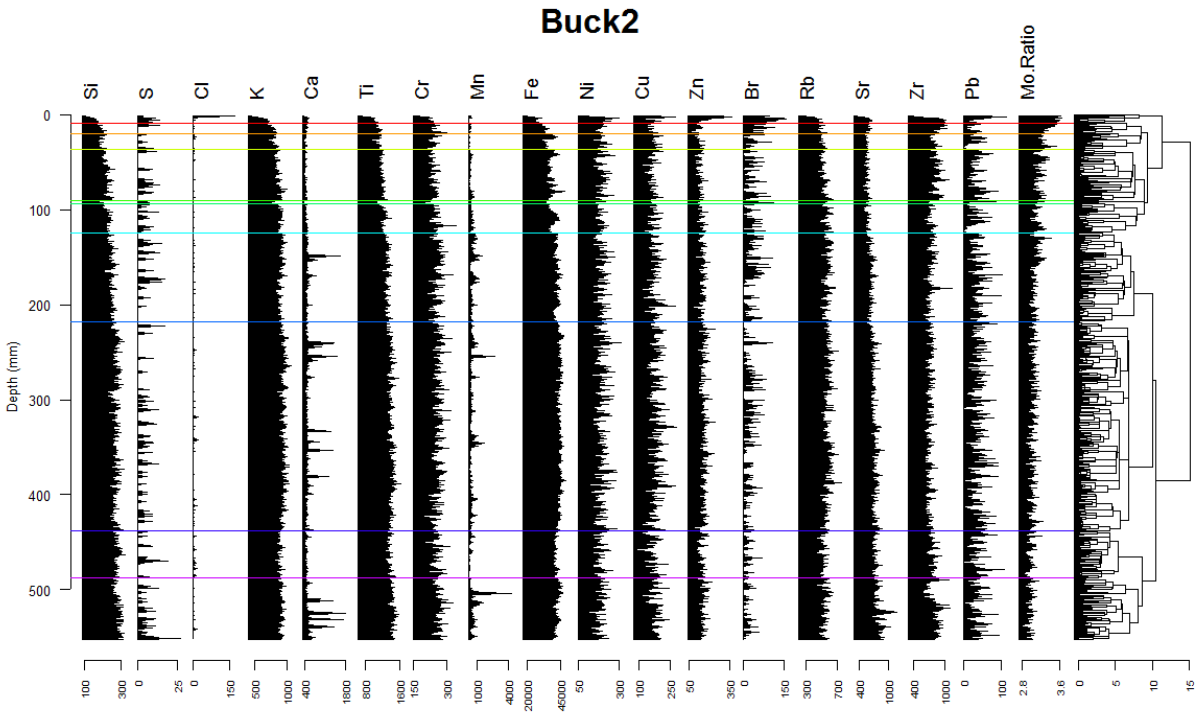
Appendix 4: Single-grain radial plots for the Equivalent dose where: (A) Buck02 20-30 cm (n = 111), (B) Buck02 42-52 cm (n = 51), (C) Buck03 30-40 cm (n = 189), (D) Buck03 75-85 cm (n = 14), (E) Will02 20-30 cm (n = 78), (F) Will03 30-40 cm (n = 17), (G) Will03 107-117 cm (n = 9).

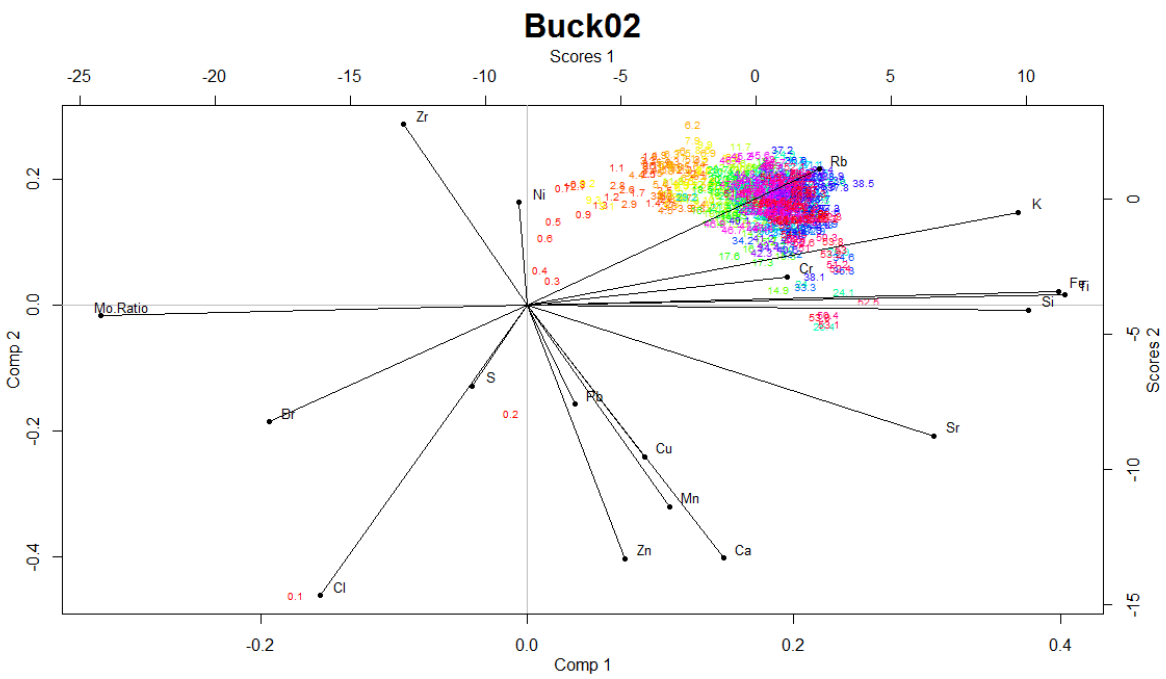
Vegetation	C_3 or C_4	$\delta^{13}C$ (‰)	Supporting literature
Phragmities australis (Common reed)	C_3	-27.4 and -28.7 -28.2, 28.0, 27.6	(Yu 2014) (Whitaker et al. 2015)
Eucalyptus camaldulensis (River Red Gum)	C_3	-30.1	(Yu 2014; Whitaker et al. 2015)
Eucalyptus coolabah (Coolabah)	C_3	-30.2	(Kelleway et al. 2010b)
Paspalum distichum (Water couch)	C_4	-13.8 to -18.7	Unpublished data cited in: (Kelleway et al. 2010a p. 90)
Typha orientailis and *Typha domingensis* (Cumbungi, Bullrush)	C_3	-31.5 -29.6	(Yu 2014) (Kelleway et al. 2010b)
Chara australis (submerged/floating/algae)	C_3	-26.6	(Yu 2014)
Duma florulenta (Lignum)	C_3	-28.5	(Kelleway et al. 2010b)

Appendix 5: Vegetation in Murray-Darling Basin in south-eastern Australia.

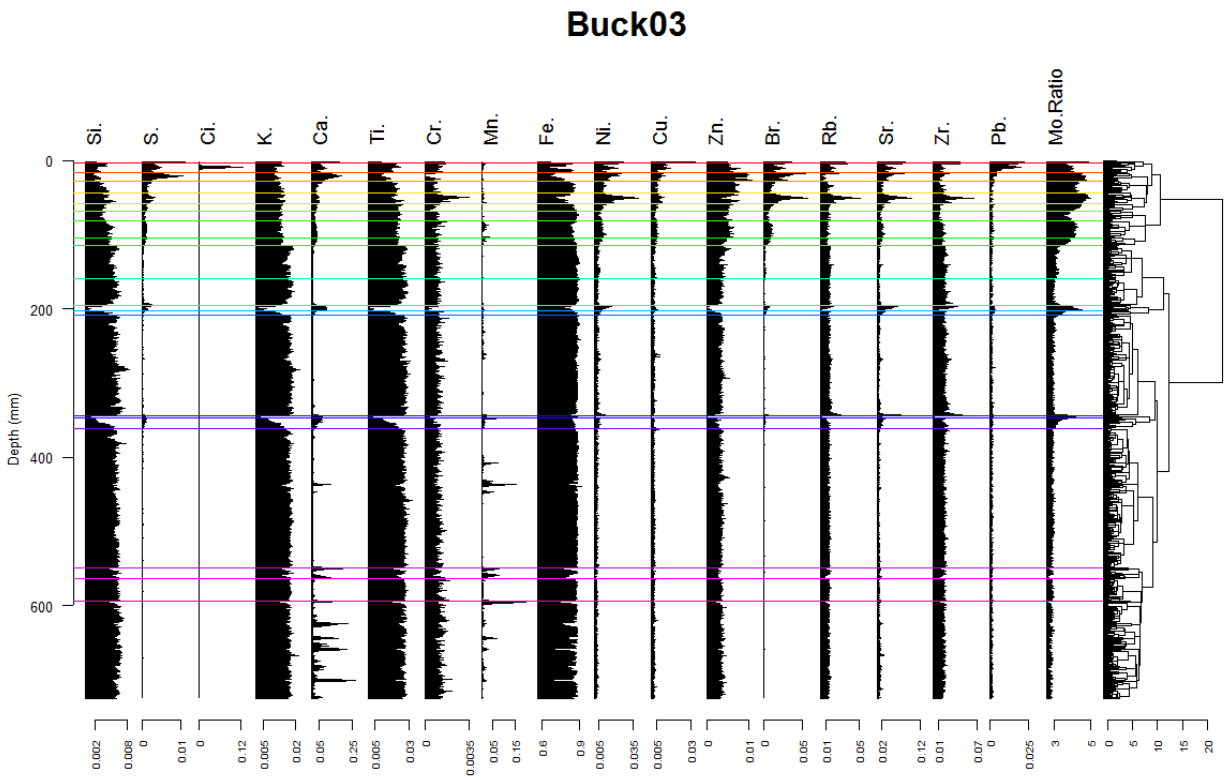


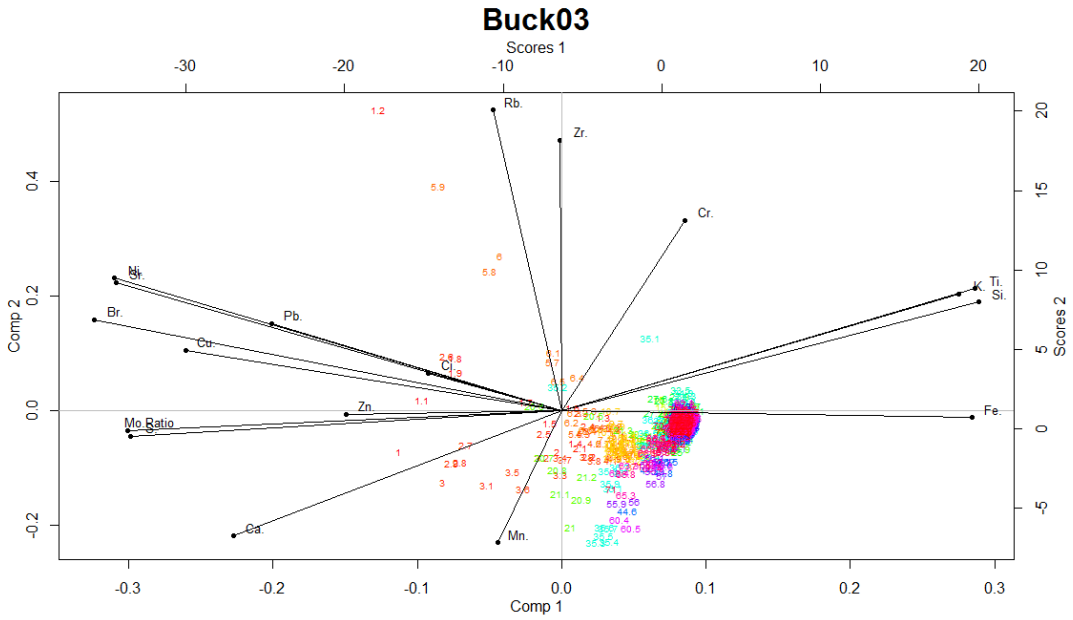
Appendix 6: Dose response curve (left) and signal decay right) curve for Buck03 (n=14/100 grains accepted.



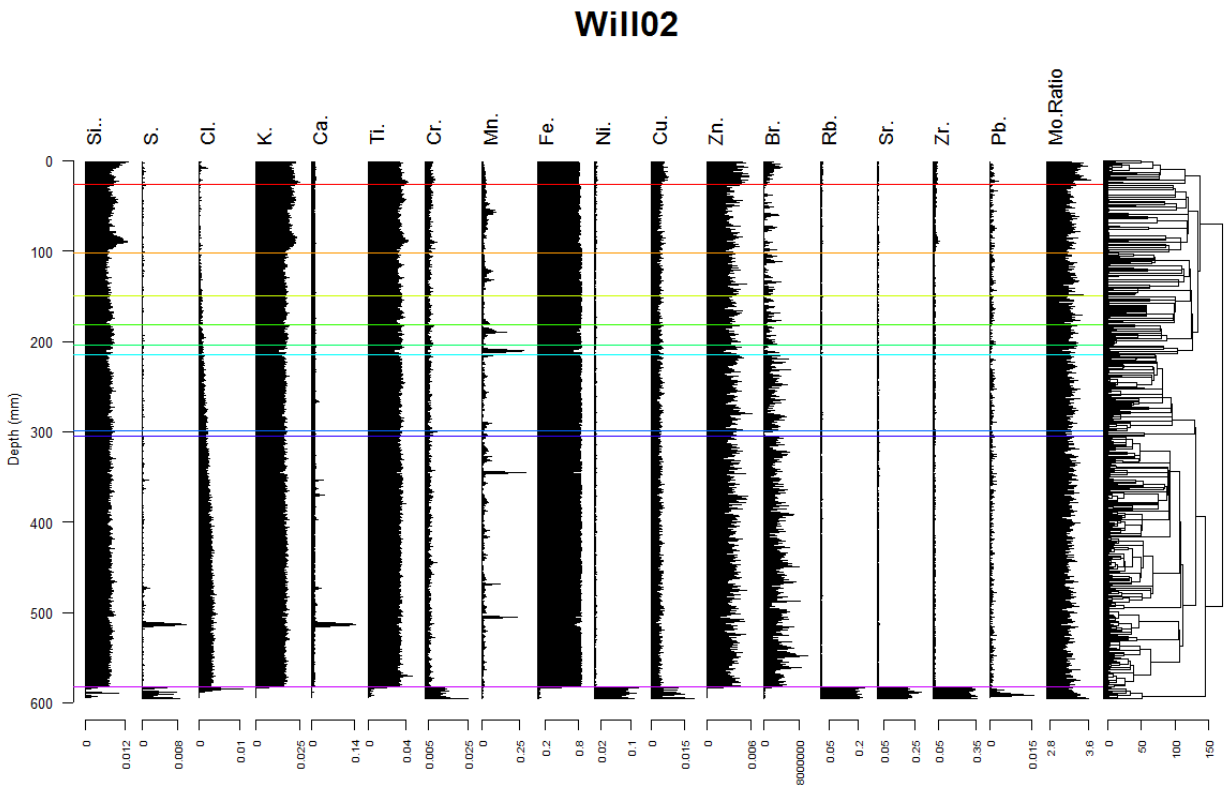


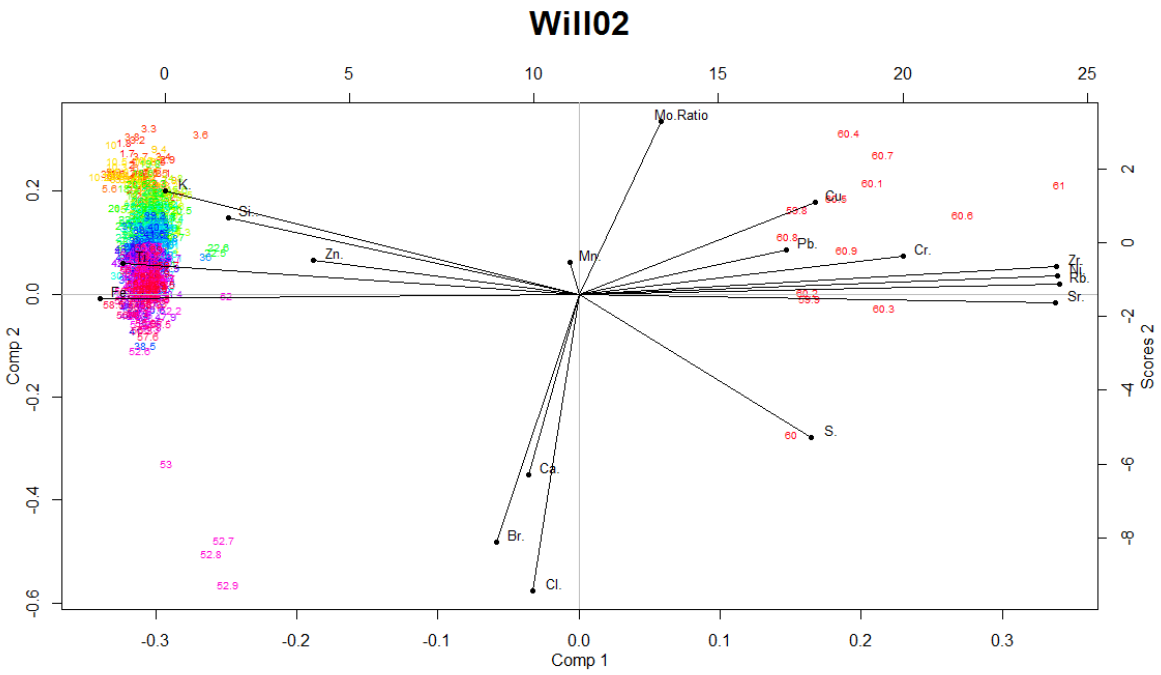
Appendix 6: Stratigraphic profile of Buck02 (top) showing geochemical elements indicating similarities and biplot (bottom) showing concentrations of elements in groups based on geochemical grouping. Coloured numbers refer to the sample depth.



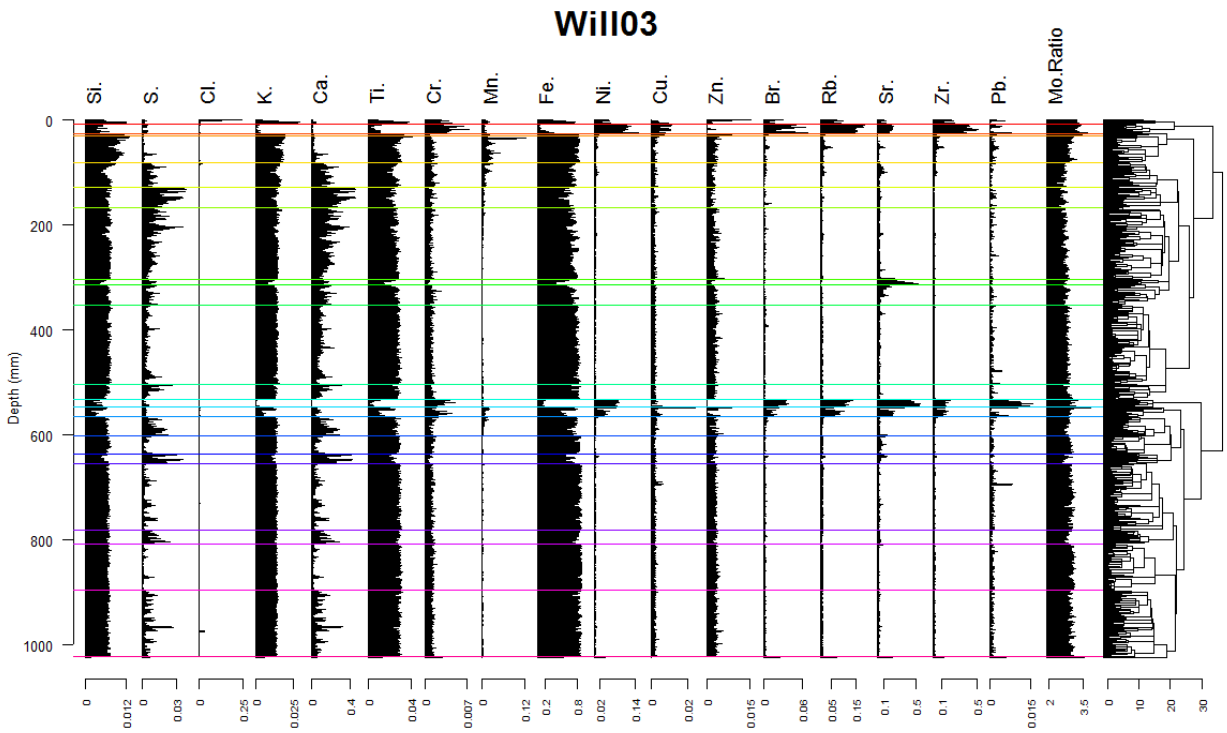


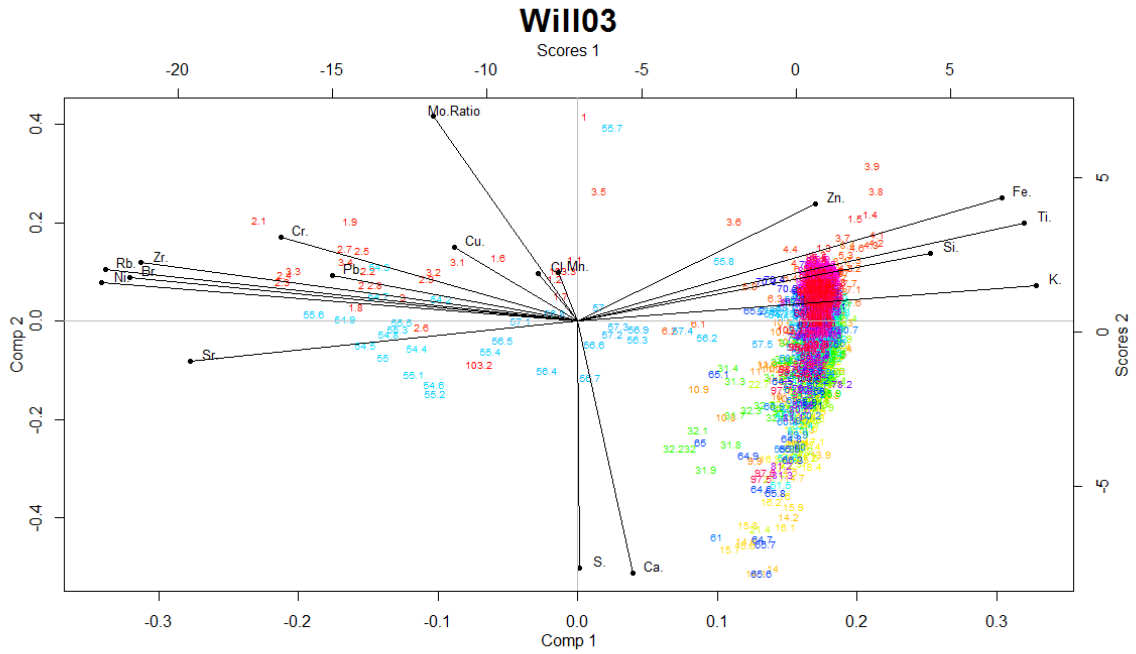
Appendix 7: Stratigraphic profile of Buck03 (top) showing geochemical elements indicating similarities and biplot (bottom) showing concentrations of elements in groups based on geochemical grouping. Coloured numbers refer to the sample depth.





Appendix 8: Stratigraphic profile of Will02 (top) showing geochemical elements indicating similarities and biplot (bottom) showing concentrations of elements in groups based on geochemical grouping. Coloured numbers refer to the sample depth.





Appendix 9: Stratigraphic profile of Will03 (top) showing geochemical elements indicating similarities and biplot (bottom) showing concentrations of elements in groups based on geochemical grouping. Coloured numbers refer to the sample depth.