Still A Million Wild Acres: Unlocking Environmental Archives in the Pilliga Forest

Old Boo wetland July 2015.

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Declaration

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

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30 October 2015

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Abstract

Land use and management in Australia can be broadly categorised into two distinct periods; pre- and post-European settlement in 1788. The Pilliga Forest is the largest remnant woodland in western NSW. It has been proposed that a shift in management regime in the post-European period caused a trophic cascade and instability in the landscape. However, these scenarios have been subjected to minimal scientific investigation. Three continuous cores were taken from three ephemeral wetlands, part of a declared 'Endangered Ecological Community' in the Pilliga National Park. Through the application of a multi-proxy approach that incorporates surveying catchment and wetland topography, limnology, sedimentology, geochronology and geochemistry, this project found that sedimentation rates have increased over one order of magnitude in the European period in Old Boo wetland. The wetland was formed ca. 15,000 years ago, as an ephemeral shallow water body and has progressively become wetter and home to a more complex aquatic community. Threats to the wetland appear to be accelerated sedimentation from forestry service tracks, rather than drying or water quality. Management plans should therefore aim at minimising sediment inputs. These findings give partial support to Rolls' model but do not point to catastrophic change as claimed.

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1.0 Introduction

The Pilliga Forest of inland northern New South Wales (NSW) was raised as an example of dramatic, perhaps catastrophic, environmental change brought about by a change from indigenous to European landscape management practices, beginning in the latter half of the 19th Century (Rolls, 1981). The Pilliga Forest is the focus of this research to unlock environmental archives of this period and to understand the trajectory of change affecting endangered ephemeral wetlands. Despite the assertion of dramatic environmental change, there has been limited scientific research within the Pilliga and little is known about the magnitude of such changes.

The dynamic nature of a human-landscape coupling required the emergence of an interdisciplinary quantitative approach (Murray et al., 2009). The study of lacustrine sediments provides valuable climate, geomorphic, hydrologic, and ecological information. In particular, how the processes and systems change in response to natural cycles and management techniques (Battarbee, 2000; Tibby, 2003). Here a multi-proxy approach was applied to address contemporary management issues, and to provide valuable baseline data of environmental change in ephemeral wetlands within the Pilliga Forest.

The aim of this research is to answer several key questions relating to wetlands in the Coghill Creek catchment. What is the trajectory of environmental change in the Pilliga Forest, and how have altered land management and fire regimes changed forest structure? Have those changes led to ecological change and caused geomorphic instability affecting the creeks, their floodplains and wetlands as described and predicted (Rolls, 1981). Therefore, to test the historical scenarios propounded by Rolls the aims of this research are to:

1. Determine the age of the wetlands in the Coghill Creek catchment; and to identify what is or was their characteristic hydrology, and the principle geomorphic processes that formed and maintained them;
2. Assess downstream geomorphological change of streams leading to the wetlands in the catchment to determine flow thresholds, geomorphic adjustments and disturbance;
3. Identify sediment sources, storage and transport zones in the Coghill Creek catchment to deduce spatial and temporal shifts in sediment deposition and erosion;
4. Evaluate the current status of the wetlands, creeks, and floodplains;
5. Develop a conceptual understanding of the biophysical processes in the Coghill Creek Catchment and the likely future trajectory of the wetlands.

The key hypotheses of this study relating to the wetlands follow:

i. The wetlands are of Holocene age and were formed by water perched above the impermeable fragipan in the subsoil of the floodplain sediments in small basins at the margins of the floodplain;
ii. Changes in hydrologic regime are primarily climate driven by the El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (wet and dry phases) (Woodward et al., 2014a; Fitzsimmons et al., 2013);
iii. Gilgai processes also modify the wetlands but do not fundamentally lead to their formation;

iv. Forestry harvesting in the catchment not only altered vegetation structure, but has caused geomorphic adjustments to streams, creeks and this threatens the wetlands downstream (Rolls, 1981);

v. Fire is a leading driver of geomorphic change in the Pilliga Forest and the Coghill Catchment as elevated sediment yield, sediment accumulation rates and aggradation in the creeks is caused by altered fire regimes (Rolls, 1981);

vi. A series of post fire high magnitude storm (>100 mm) or flood events can potentially infill the wetlands due to high sediment yields generated from bare hillslopes in the catchment (Shakesby and Doerr, 2006);

vii. Forestry service tracks/roads are a major contributor to sedimentation in these micro depositional wetland environments during low magnitude storm events (Motha et al., 2004; Fu et al., 2009).

1.2 Significance

The Pilliga Outwash Ephemeral Wetlands were recently deemed a 'threatened ecological community' based on their uniqueness, assemblage of species, a very limited geographic range and several major threats including wild pigs, weed invasion and clearing vegetation (NSWSC, 2014). The key threatening processes include altered hydrology where many wetlands have been drained or filled by sedimentation, land management practices such as logging, and anthropogenic climate change. A reduction in surface water and prolonged periods of drought may reduce the ecological functioning of the wetlands and cause extinction (Bell et al., 2012; NSWSC, 2014).

The management of the Pilliga Forest has two distinct periods; pre-European (ca. 45 ka – 1830 and post-European (1830 - present) (Rolls, 1981; Gammage, 2011). The techniques used were guided by traditional ecological knowledge of the Gamilaraay, and by entrepreneurial pursuits of early explorers that sought to establish an agricultural industry. Despite the long history of anthropogenic influence, it is claimed that a dramatic ecological change has occurred more recently as a direct result of European management (Rolls, 1981). The change in fire regime and extinction of keystone species has caused two trophic cascades which altered the vegetation structure and cascades of geomorphic instability. Fire suppression and exclusion within the extensive commercial forestry protected the valuable fire sensitive *Callitris glaucophylla (Callitris*) resources. It is argued that La Niña events in the 1880s and 1950s led to rapid regeneration which created the modern Pilliga (Rolls, 1981). Dense same age stands have 'locked up' the forest, making it denser in a fire prone environment which now required intensive active management. Attitudes towards ecological thinning and opposing views on land management have proven to be a contentious issue often played out in public discourse (Ryan et al., 1995; Benson and Redpath, 1997; Butzer and Helgren, 2005).

It has been proposed that the legacy of European management now threatens the endangered wetlands even in protected areas (Rolls, 1981; Bell et al., 2012; NSWSC, 2014). The shared use of the Pilliga means that forestry operations continue in the Coghill Creek catchment which flows through the Pilliga National Park. It has also been proposed that increased sediment yields within the catchments is associated with commercial forestry operations and are generated from intensive fires, mobilised from the bare hillslopes and is accommodated in the creek and valley margins (Rolls, 1981). A high magnitude storm event (>100 mm) could surpass the flow threshold and activate the ephemeral drainage network thereby liberating and transporting a blanket of sediment (slug) down catchment (Tomkins et al., 2008). The synergy between a flashy flow regime, the loss of surface roughness from fires and altered soil properties hasten surface flow and increase entrainment could potentially infill the wetlands (Shakesby and Doerr, 2006).

This study provides a platform for Environmental Science to inform management of their history, trajectory of change and the implications for the wetlands longevity on the floodplain. Moreover, it can enlighten agencies about landscape responses and adjustments to disturbance in light of pending climate change. The findings may fill existing knowledge gaps, challenge views of land management in the region, and scientifically quantify anecdotal evidence and historical accounts.

1.3 Research approach

This chapter outlined the research aims, hypothesis and the significance of the wetlands. Chapter 2 is a literature review that explores the Aboriginal and European management regimes on Australian landscapes, their subsequent impacts and discusses recent research to test the hypothesis (i-vii). Chapter 3 describes the regional setting and the anthropogenic history of the Pilliga Forest, Coghill Creek catchment, the ephemeral wetlands and introduces contemporary issues. A multi-proxy interdisciplinary analysis was implemented to ensure robust research outcomes could be made. The wetlands' topography, sedimentology, geochemistry and geochronology were investigated, and examination of the surrounding creeks, flood plains and hillslopes provided evidence at the local and catchment-scale. Chapter 4 explains the sampling strategy and analytical methods used for this research. Chapter 5 describes the results from this research which are discussed in Chapter 6. The conclusions and major findings are summarised and presented in Chapter 7.

2.0 Literature review

2.1 Palaeoclimate and Aboriginal colonisation

Before human occupation, climate change in the Quaternary period has undoubtedly been a primary driver in transforming the landscape and influencing Australia's earth surface processes. The Australian continent is fire prone and sclerophyllous vegetation is widespread, except for the wettest biomes (Bowman, 1998; Bradstock, 2008). The morphological features of such vegetation, enhanced tolerance to drought and resilience to frequent fires are said to have evolved in the late-Pleistocene long before human occupation (Singh and Geissler, 1985). Current archaeological evidence derived from radiocarbon and Optical Stimulated Luminescence (OSL) dating places the beginning of Aboriginal and Torres Strait Islander colonisation of Australia in the late Pleistocene (45 ± 5 ka) (Bowler et al., 2003; Olley et al., 2006). By the mid Holocene (5 ka) the entire continent and its diverse landscapes were inhabited. The intervening period encompassed distinct glacial, deglacial and interglacial phases where palaeoenvironmental research reveals a spatially and temporally variable climate (Hesse et al., 2004). The mid Holocene (9-6 ka) was distinguished by higher rainfall followed by a much drier period which is associated with the onset of ENSO (Fitzsimmons et al., 2013). These ocean-atmosphere interactions and enhanced atmospheric circulation are connected with the modern day cyclic wet and dry phases – La Niña and El Niño which caused prolonged droughts, enhanced conflagrations and sporadic large flood events (Daniau et al., 2012; Fitzsimmons et al., 2013).

2.2 The Fire Stick Farming hypothesis (45 ka – 1788)

Land Management in Australia can be categorised into two distinct periods; Pre and Post-European settlement (45,000 to 1788; 1788 – 2015), and by people with vastly different management techniques (Bowman, 1998). The association between Aboriginals peoples and fire is recorded in various colonists' journals and is depicted in paintings during early European colonisation (Vigilante, 2001; Semple, 2011; Gammage, 2011). Captain James Cook's exploration of the Australian east coast in 1770 noted 'smooks in the day and fire by night' (Wharton, 1893). After the arrival of the First Fleet, Governor Phillip noted 'natives so frequently setting fire to the country' and Governor Bligh recounted 'fires made by natives' (Corsley, 1962). Major Ludwig Leichhardt observed that fire 'attracts game to particular spots', Thomas Mitchell noted that 'fire, grasses, kangaroos and human inhabitants all seem dependant on each other'; Ernest Giles remarked 'burning, burning ever burning' and John Oxley thought 'numerous smokes from natives fires announced a country well inhabited' (Mitchell, 1839; Giles, 1889; Oxley, 1820; Pyne, 1990). These accounts gave an insight into existing management techniques that recognised burning was common, perhaps a deliberate act within a management framework. Debate persists about how widespread its use was and the scale of impacts (Rolls, 1981; Flannery, 1994; Gammage, 2011).

In Northern Australia, Aboriginal culture and practices are much better preserved than southeastern Australia. Rhys Jones (1969) coined the phrase 'Fire Stick Farming' from observing how the Aboriginals (traditional custodians) interacted purposefully with seasonal and landform variations to implement resource management strategies. To summarise a popular narrative, the primary tool was fire and its frequent or selective use allowed the landscape to be modelled into templates or patch mosaics that established and maintained predictable and sustainable resources. Through multiple generations of occupants' traditional ecological knowledge, was passed down and developed into an intricate understanding of the various landscapes; their climate, fauna and flora (Jones, 1969; Gammage; 2011). However, it has been argued that over evolutionary timescales Aboriginal fire regimes created a series of impacts that led to the extinction of the megafauna and changed the life histories and traits of vegetation communities (Pyne, 1990; Flannery, 1990; 1994). These disturbances favoured fire tolerant *Eucalyptus* species, determined geographical ranges that led to local and regional extinctions of rainforests and casuarina dominated communities and pyrodiversified the landscape (Singh and Geissler, 1985; Trauernicht et al., 2015).

Interestingly, Bowman (1998) suggests that anthropogenic burning was not the main driver of change and highlights the difficulty in demonstrating an ecological role, a systematic and informed approach by the Aboriginals to fire application. A study by Mooney et al. (2011) found no correlation between archaeological evidence, commencement of inhabitation and biomass burning. In contrast, it is generally accepted that the Aboriginals adopted a high frequency-low intensity fire regime to clean the country. However, this is based upon a paucity of temporal and spatial data and is poorly preserved in the charcoal records (Bowman et al., 2004). Despite the fact that traditional ecological knowledge is well preserved in the Northern Territory and customary land management is still widely practiced (Russell-Smith et al., 1997; Bird et al., 2008), when one considers the different climate and poor preservation of traditional ecological knowledge in southeastern Australia, extrapolating the fire paradigm from prehistory to the entirely different conditions of the present in south eastern Australian and elsewhere should be done with caution (Bowman, 1998).

2.3 European contact and colonial expansion (1770-1850's)

The European period (1788 – present) began with the establishment of the colony in NSW and the early settlers embarked on a concerted effort of expansion that established a self-sustaining colony by implementing European land management systems (Butzer and Helgren, 2005). The Cumberland Plain, west of Sydney, with its clay soils and open landscape (maintained by frequent Aboriginal burning) was suitable for agriculture, although cumulative pressures of population growth, increased stocking rates, caterpillar plagues and drought brought a downturn in productivity (Gale and Haworth, 2002). Expansion was warranted when it was discovered the soils elsewhere were thin and of low quality. Governor Macquarie hastened the exploration beyond the Sydney Basin for suitable agricultural lands (Gale and Haworth, 2002).

The westerly encroachment led to the crossing of the Great Dividing Range in 1813 and new frontiers were opened up in the Central, Southern and Northern Tablelands. Despite the early promise, settler's soon realised conditions were not dissimilar to those previously experienced in the Sydney Basin, except rainfall was even lower over the mountains (Butzer and Helgren, 2005). The combination of variable climate, unreliable rains and pastures; the effects of poor soil management and foreign hooved stock compacting soil, erosion from grazing the ground bare and clearing of vegetation by ring barking accelerated environmental degradation of the rangelands and beyond (Butzer and Helgren, 2005).

2.3.1 Scientific debate: environmental history

Early accounts described a vast landscape of open forest and lush grasslands that resembled a nobleman's park as opposed to natural forest. Trees were well spaced and the understorey was free from dense shrubs; the grasslands were supported by dark and spongey soils; they were bordered by brooks with gravel beds and thinly wooded hills (Rolls, 1981). In essence, they discovered a familiar land that was deemed suitable for agriculture (Ryan et al., 1995). It is believed that Europeans altered the fine balance created through ongoing Aboriginal maintenance by dramatically changing fire regimes; in particular, the frequency, intensity, spatial and temporal patterns or variations between landscapes (Gammage, 2011). Specifically, the exclusion and ad hoc application of fire affected vegetation communities and their structures by transforming them from open grasslands to dense forests. Conversely, other historical accounts identified dense scrub and forests at the time of settlement (Benson and Redpath, 1997).The issue of regrowth became politically charged in the 1990's as farmers and conservationists pushed their agendas to influence policy. Differing management philosophies and practices (active or passive) sought to protect forests in a state that arguably did not exist prior to European settlement, and others sought to clear it for agriculture and use prescribed burns to create natural conditions or protect forestry assets (Griffiths, 2002; Jurkis, 2000).

2.3.2 Catastrophic adjustments to European management regimes

A shift in land management techniques is believed to have caused widespread geomorphic, hydrological and ecological change and in some instances was catastrophic. The changes can create a cascade of negative outcomes to both abiotic and biotic components of earths' surface, and have been directly linked to exploitive practices such as agriculture and forestry (Butzer and Helgren, 2005). An exponential increase in sediment generation along NSW's tablelands has caused what is referred to as post settlement alluviation (PSA), and more recently defined as legacy sediment (Prosser et al., 2001; Walling, 2006; James, 2013). In essence, sediment fluxes in fluvial systems and disturbances in their catchments such as the removal of riparian vegetation and increased runoff are artefacts of post-European settlement. The response to management regime change typically instigated gully erosion, increased sediment yields and altered river morphology (widening and shallowing). A peak in sediment flux occurs rapidly after disturbance and this generally declines whilst remaining above pre-European levels as gully networks reach maximum extension (Wasson et al., 1998; Olley and Scott, 2002; Olley and Wasson, 2003). The transport of sediment downstream depends on the connectivity of the system as hydrologic efficiency influences accommodation in geomorphic units or dispersal throughout the catchment from uplands into the lowlands in a source-sink relationship (Fryirs and Brierley, 2001; Fryirs, 2013).

Butzer and Helgren (2005) broadly examined the environmental history of the NSW Tablelands to address environmental degradation through a century of European pastoralism, and found no support for an apocalyptic model of impacts that is widely accepted. Landscape recoveries have been observed in the Southern Tablelands as gullies become revegetated, a buffer forms trapping sediment inhibiting its movement (Rustomji and Pietsch, 2007); and palaeoenvironmental reconstructions at Little Llangothlin Lagoon in the Northern Tablelands also provides an interesting counter argument. The findings of the earlier studies suggested that Europeans were in the New England as early as 1820 and logging the catchment (Gale et al., 1995; Gale and Haworth, 2002). However, more recent evidence challenges the notion that Europeans were present at that time or that their activities were responsible for an erosion event identified in the sediment cores (Woodward et al., 2014a). The evidence derived from macrofossils, macroscopic charcoal and sedimentology found the sedimentation in the lagoon pre-dates settlement. Moreover, the change is attributed to the strengthening of ENSO wet and dry cycles reflected in the depth of and permanency of water. Therefore, climate was considered to be the primary driver of environmental change, discounting the Aboriginal-European management transition as the trigger of a cascade of negative outcomes.

2.4 Positive feedbacks in the Pilliga Forest since the 1850's

Rolls (1981) in his seminal book 'A Million Wild Acres' outlined the paradigm of changing vegetation structure, forest encroachment and increased shrub densities. Rolls argued that this was due to land management techniques and claimed that (European) man made the forest. The exclusion of fire and two major regeneration episodes that followed wet ENSO phases (1880's and 1950-51) led to the establishment of thick stands of *Callitris*. With a reduction in grazing pressures due to the extinction of the Rat Kangaroo and reduction in rabbit numbers, the landscape was 'locked up' and colonisers abandoned agricultural lands.

An effort to develop grazing runs in the Pilliga Forest occurred in the mid-1830s but was limited to the fringes and south western edges around Baradine due to poor sandy soils and lack of suitable grazing (Rolls, 1981). Therefore the central area of the Pilliga Forest has never been cleared for agriculture but has instead been used for commercial forestry. The historical accounts discussed above describe a natural open forest / woodland with well-spaced trees, a limited shrubby understory and ample supply of perennial grass on fertile black basalt soils of the Liverpool Plains. This instigated development of agriculture in the Namoi Valley.

The shift from a forest managed for economic gain to national parks estate or nature reserves has led to a decline in active management. To protect assets and maintain a commercial forest's viability, specific tasks such as mechanical thinning, or burning and creating fire breaks take place. A passive management approach could have been responsible for a fire regime of high intensity increasing in frequency where fuel loads permit (Jurkis, 2005). However, prescribed burning is also undertaken as part of a conservation management regime. Typically, these are implemented in cooler months to create asset protection zones, to protect property and to shepherd fires away from urban areas or main arterial roads. Biodiversity is said to be enriched by patch burning, as per fire stick farming and this remediates the landscape (Jurkis, 2000). Conversely, a landscape's biodiversity may deteriorate when the intervals between fires are not conducive for establishment and regeneration, and this may favour more resilient species (Benson and Redpath, 1997; Bradstock, 2008). A growing trend in Australia and elsewhere is the incorporation of indigenous biocultural knowledge into contemporary management plans that contribute to biological conservation priorities (Ens et al., 2015).

2.4.1 Research frontiers in Geomorphology: revisiting 'A Million Wild Acres'

Rolls' hypothesis has never been scientifically tested in the Pilliga Forest but is generally accepted as fact, and has been influential in providing a clear rationale for management actions of thinning and land clearing. A study that incorporates a robust multi-proxy methodology and advanced techniques may disentangle the matter by empirically quantifying the evidence, inform management and guide policy. The Pilliga Forest provides an appealing site to conduct research and to utilise an interdisciplinary multi-proxy methodology because of the human-fire-vegetation interplay, climate change and ongoing scientific debate (Rolls, 1981; Flannery, 1994; Ryan et al., 1995; Benson and Redpath, 1997). Recent studies relate to vegetation thickening, its structure and the fire-vegetation feedback loop (Norris et al., 1991; Lunt, 2002; Cohn et al., 2011).

The changes in vegetation structure were scientifically validated by comparing forestry inventories from the 1940's to stands in 2005, and by assessing how disturbance from fire affected structure and dynamics in different forest types (Whipp et al., 2012). The study found that there had been a three-fold increase in density and a four-fold increase in basal area within two forest types in the 60 year period. These results were consistent with regeneration events, 'locking up' and continued *Callitris* encroachment identified during the 1800's by others. The implications of such findings were that active management 'thinning' was required to maintain forest productivity. The voracious debate about environmental history remains in a stalemate because there is evidence to support and refute both view-points about fire regimes. It is accepted that fire is a genuine management tool in various land tenures, but its use to mimic natural regimes, whatever they were and their impacts remains unclear. Therefore, its application should be underpinned by scientific evidence and should not be reliant on anecdotal, historical accounts or untested hypothesis to meet management objectives.

Developing an understanding of environmental impacts from management techniques is paramount for establishing a cause, effect and long term response link within the biophysical landscape. Generally, studies focus on pre and post disturbance regimes and how the landscape evolved and more recently anthropogenic geomorphology (Szabo, 2011). In reconstructing palaeoenvironments, sedimentary cores are extracted from lakes or lagoons because they retain archives of past conditions that can be placed into a chronological framework (Mills et al., 2013). This allows the deduction of geomorphic, ecological, hydrological and geochemical change in catchments during the Holocene and inferences can be made relating to impending climate change, and how it will affect floodplain wetlands in the Murray–Darling Basin (MDB) and elsewhere (Gell et al., 2013).

3.0 Regional setting

3.1 Study area: Pilliga Forest

The Pilliga Forest is approximately 650 km northwest of Sydney (30.42˚–31.25˚S, 148.67˚–149.83˚E). It is situated between the townships of Narrabri to the northeast, Coonabarabran to the south and Baradine to the southeast (Fig 3.1). At around 500,000 ha, it is the largest remnant of semi-arid temperate forest and woodland west of the Great Dividing Range in Eastern Australia and is part of the MDB (Murphy, 2011). The area has significant heritage, cultural, conservation, scientific and education values (Kavanagh et al., 2007; Murphy and Shea, 2013; Mo, 2014, OEH, 2014). Key conservation attributes are its size and relatively intact condition despite widespread clearing in the wheat-sheep belt west of Narrabri. It includes two interim biogeographic regionalisation of Australia (IBRA) provinces in the Brigalow Belt South Bio-Region (BBS): the Pilliga Sandstone and Pilliga Outwash (NPWS, 2000; OEH, 2015a). The Pilliga has been identified as part of the forests of east Australia biodiversity hotspot plus an important bird area (Williams et al., 2011; Department of Environment, 2015). It provides a refuge for flora and fauna, and a corridor joining the Kaputar and Warrumbungle ranges national parks. Several species and ecological communities that occur within the Pilliga are recognised as vulnerable, threatened or endangered under relevant state or federal government environmental protection legislation (NSW Government, 1995; Australian Government, 1999). Past and current anthropogenic land use has impacted the area, with clearing for agriculture on the fringes and forestry operations in the interior. The proposed establishment of an extensive coal seam gas (CSG) field, expansion of and planned coal mines at Whitehaven and Maules Creek has overarching implications at the global scale.

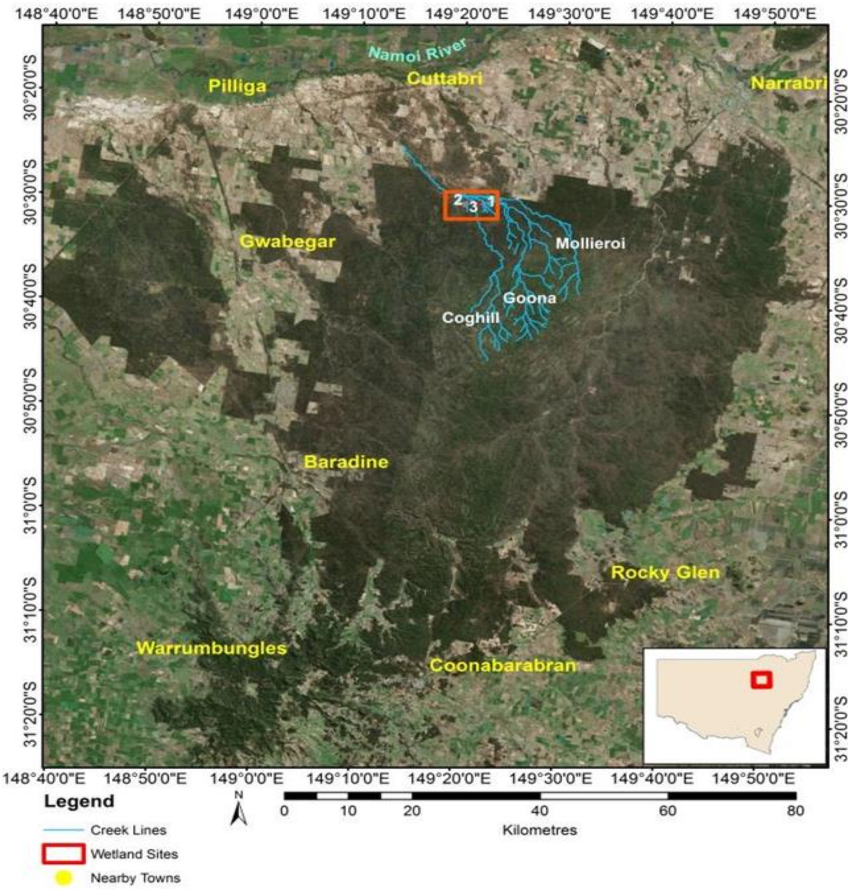

***Figure 3.1**: A map of the Pilliga Forest with the latitude and longitude along the border of the figure. The study area to the north is boxed in red and the sites are numbered in white. The major creek lines (labelled in white from left to right Coghill, Goona and Mollieroi) in the catchment draining into the wetlands. The nearby townships of Narrabri (northeast), Pilliga (northwest), Coonabarabran (southeast); Baradine (southwest) are marked in yellow. The Namoi River is to the north (blue) and the Warrumbungle Ranges to the south. The area of the forest to the south and east is formed in Pilliga Sandstone. To the north and west is the Pilliga 'outwash', an area of alluvium derived from erosion of the Pilliga Sandstone.*

3.2 Climate and vegetation

The Pilliga Forest has a sub-humid to semi-arid climate, which is typical for the region, and sits on the border of the sensitive temperate and semi-arid Koppen climate zones (Stern et al*.,* 2000). Generally, considerable seasonal variations are observed; the mean high and low temperatures for Narrabri West Post Office in January is 33.8˚C to 20.2˚C and for July is 18.0˚C and 3.7˚C (Fig 3.2A). For the same months the maximum and minimum temperatures can reach 43.4˚C and -4.4˚C respectively (BOM, 2015a), with frost developing during cooler months. The average annual precipitation is 646 mm dominated by a summer peak and followed by a transition to lower rainfall from April until September (Fig 3.2A) (BOM, 2015a). The average annual potential evaporation rates are 1600 mm and this exceeds annual precipitation such that soils are commonly dry and runoff occurs only after intense storms. A combination of decreased cloud cover, warmer daytime temperatures, and lower rainfall in winter and spring can result in a higher frequency of bushfire in the area. The dominant wind originates in the east and southeast, especially in summer (Fig 3.2B). Extensive drought and wetter periods in eastern Australia are correlated with ENSO cycles; likewise the increase in extreme weather events including heat waves, catastrophic fire storms and sporadic floods (Murphy and Timbal, 2008).

There are 39 distinct vegetation communities in the Pilliga Forest consisting of: Tall and open dry sclerophyll forests; tall, open, shrubby and grassy woodlands; tall and mallee shrub lands, sedge lands, rush lands and gilgai wetlands (Benson et al., 2010). The canopies are dominated by several species including: Narrow-leaved Ironbark (*Eucalyptus crebra*), Broad-leaved Ironbark (*Eucalyptus fibrosa*), Pilliga Box (*Eucalyptus pillagensis*), White Cypress Pine (*Callitris glaucophylla*) and Buloke (*Allocasuarina luemannii*) with diverse shrubby and grassy understory associations of varying densities (Benson et al., 2010). The differing communities are mostly found on sandstone ridges, hillcrests and alluvial landforms. The majority of natural vegetation on the Pilliga Forest fringing fertile lands has been cleared for farming. Commercial forestry operations harvest *Callitris* and *Ironbark (Eucalyptus sp.)* stands from the less arable interior.

3.2.1 Geology, soils and landforms

The Pilliga Forest is located within the Coonamble Embayment, part of the Surat Basin (Geoscience Australia, 2013). The Coonamble Embayment was formed by down warping of northern NSW during the late Triassic period (Ardito, 1982). The major sedimentary formations are; the Jurassic Pilliga Sandstone and underlying Purlewaugh and Orallo Formations. The Pilliga formation is a quartzose sandstone and conglomerate with minor interbeds of mudstone, siltstone and fine grained sandstone and coal. The characteristics of this formation are a medium to very coarse grained, well sorted, angular to sub-angular with carbonaceous fragments, iron staining with rare lithic fragments (Geoscience Australia, 2014). The Pilliga Forest is underlain by and is a major recharge zone for the Great Artesian Basin (GAB), which is one of Australia's most important and heavily exploited water resources (GABCC, 1998; Rolfe, 2010). The alternating layers of non-marine permeable quartzose sandstone and impermeable marine siltstone and mudstone make Pilliga Sandstone one of the major water bearing aquifers in the GAB (Hennig, 2005; O'Shea and Jankowski, 2006).

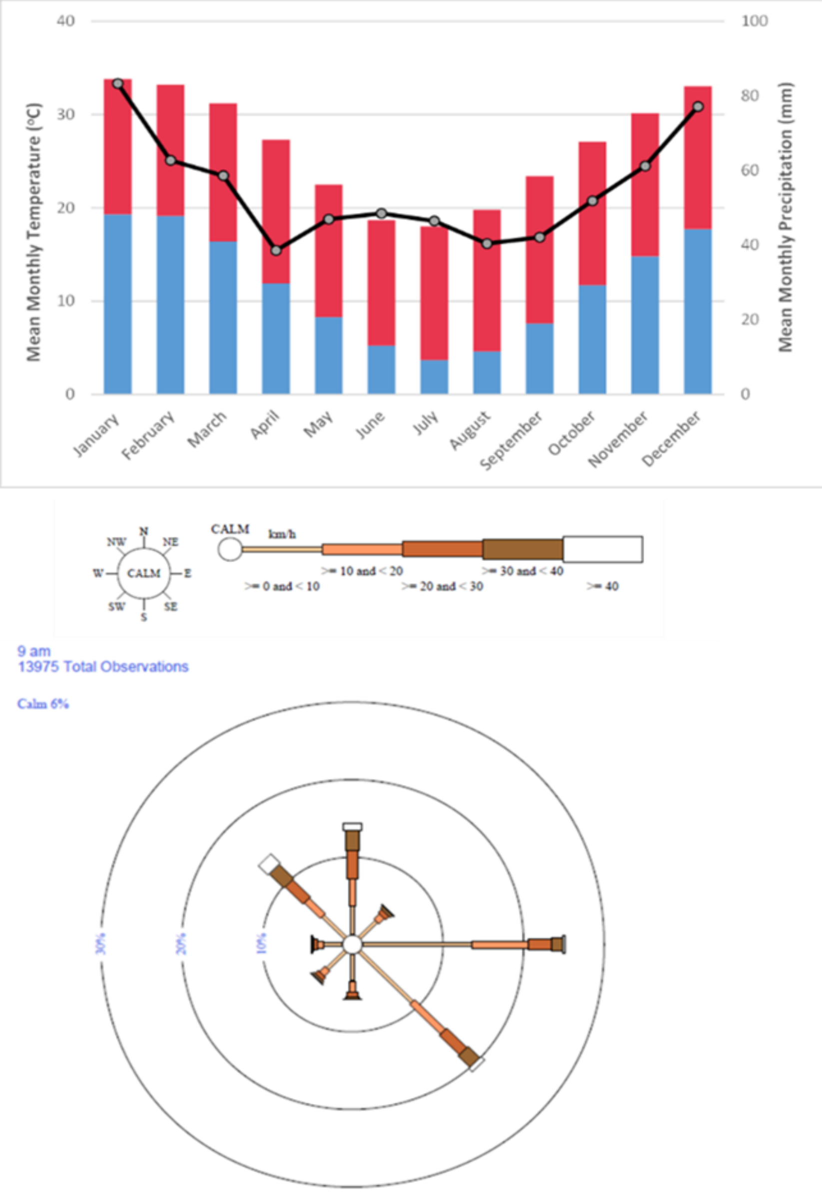

Figure 3.2: ***(A)*** *Mean temperature (bars: maximum and minimum) and precipitation (black line);* ***(B)*** *Prevalent wind direction at 9 am Narrabri West Post Office. (Source, Bureau of Meteorology http://www.bom.gov.au /climate/averages/tables/cw_053030. shtml)*

Soils in the Pilliga can be grouped into the following categories: Solodized-solonets, Lithosols, Deep Sands and Sierozerms. The duplex texture contrast soldized-solonets (Newell; Talluba; Merrindi and Yarrie) have a sandy loam topsoil with a clayey subsoil and are the most widespread. Lithosols are thin, rocky and limited to sandstone hillslopes or ridges; red or yellow deep sedimentary sands occur in the abandoned channels (sand monkeys) in the Coghill Creek and elsewhere, and Sierozerms are deep heavy clays found in the northern band of gilgai wetlands (Hallsworth and Waring, 1964). The different soil groups support different vegetation communities throughout the park (Hesse, 2000; Humphreys et al., 2001), and the wetlands described in section 3.4.1 occur mostly in alluvial soils bordering Coghill Creek.

3.3 Pre European land use

The traditional indigenous owners of the lands were the Gamilaraay people who have inhabited the Namoi Valley, the Pilliga Forest and surrounding areas for several thousand years. There is evidence of a permanent settlement in the region with caves providing seasonal dwellings, where cave paintings indicate hunting or ceremonial grounds, and the use of rock grooves for tool preparation (Humphreys, 2007; OEH, 2012). Although little ethnological evidence has been preserved, it is thought that Gamilaraay inhabited the areas around the creek lines and adhered to the fire stick farming technique that are still practiced in the Northern Territory and elsewhere (Jones, 1969; Bowman 2001; Vigilante, 2001; Bird et al., 2008). Early explorers into the area described an open grassy landscape with fewer trees, much different to the dense forest of today (Rolls, 1981; Oxley 1820). Their occupancy is thought to have been underpinned by frequent burning to influence the fabric of the landscape. Resources were maintained by forming landscape templates that ensured the predictability and ongoing availability of prey and other resources (Gammage, 2011).

3.3.1 Post European land use

The westerly encroachment by British settlers led to the crossing of the Great Dividing Range in 1813 and with the leading edge of explorers new frontiers were opened up in the central tablelands and northwest slopes. The Pilliga was first explored by John Oxley in 1817 and other accounts described a vast landscape of open forest and lush grasslands that resembled a nobleman's park (Oxley, 1820; Rolls, 1981; Benson et al., 2010). Squatters soon established an unofficial presence where claims and runs were set up on prime lands alongside watercourses. By the 1830-40s the margins of the Pilliga were largely divided into leasehold grazing properties and heavily stocked by cattle and later sheep, but the interior remained relatively intact (Rolls, 1981; van Kempen, 1997). However, despite the early promise, a combination of a variable climate, poor sandy soils, lack of reliable water sources and scarce rainfall saw most runs abandoned. A period of higher rainfall and the first rapid regeneration of the forest saw most runs reclaimed by the forest by the 1880s (Rolls, 1981; Norris et al., 1991).

3.3.2 Commercial forestry: selective logging

Timber regulation began in 1887 when forestry reserves were established in part of the Coghill run (area of this study) and elsewhere for the commercial extraction of valuable timber (Whipp, 2009). The selective logging of *Callitris* was used for doors and floorboards; and later *Eucalyptus crebra* and *fibrosa* (ironbark) was cut into sleepers for use on the railways (Fig 3.3AB). By 1937, the majority of the Pilliga was gazetted by the Forestry Commission of NSW (Whipp, 2009). The Forest management techniques suppressed fire and thinned *Eucalyptus* to protect the sensitive *Callitris* and aimed to increase timber yields of similar aged stands. A subsequent major regeneration event occurred in 1950-51, as higher *Callitris* densities 'locked up' large areas, changed the forest structure and, it is argued, created the modern Pilliga (Rolls, 1981). Forestry operations still continue at present in the Baradine sawmill however they have declined considerably due to economic pressures, high management costs, limits to supply and slow growth rates.

Despite harvest quotas being in place since the 1920s and reinstated in the 1950's contemporary loggers have increasing difficulties in meeting such agreements within sustainable management plans (Forests NSW, 2008). With a decrease in supply, less area open to logging, past unsustainable practices (harvesting to frequently and of young saplings), and timber quota pressures threaten to destroy the Pilliga forestry industry

(NRC, 2014; ABC, 2015). It has been suggested conservation areas will need to be reopened for logging and ecological thinning, used to underpin the rationale for clearing vegetation (Fensham, 2008), is recommended in sections to maintain the viability and health of the ecosystem (NRC, 2014; ABC, 2015).

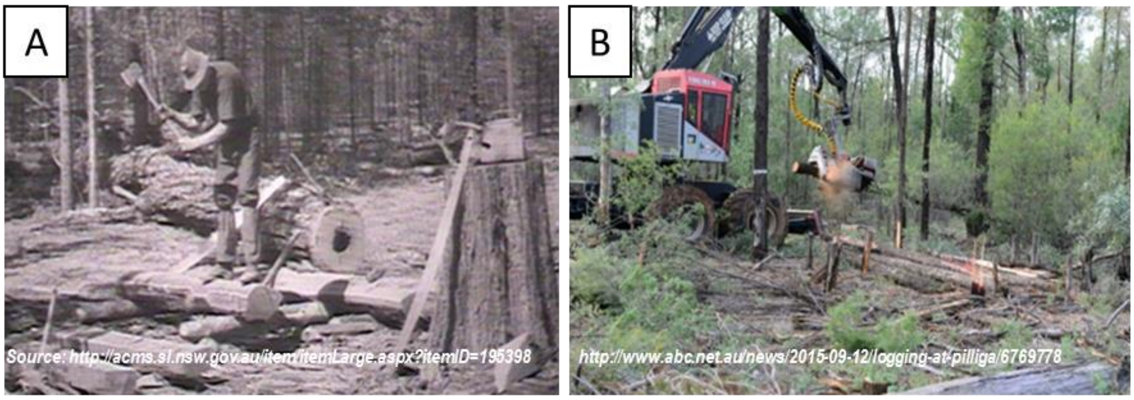

***Figure 3.3**: **(A)** Sleeper cutting, and **(B)** mechanised harvesting in the Pilliga.*

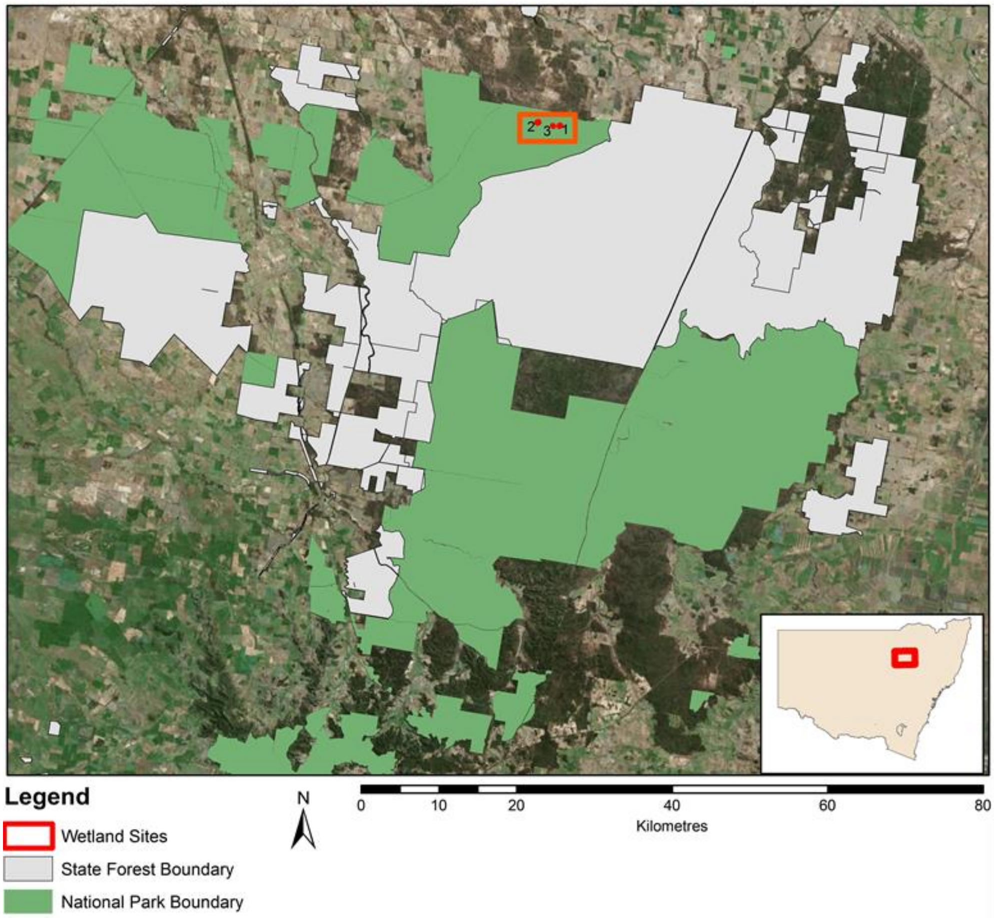

***Figure 3.4**: A map of the Pilliga Forest with the current National Parks and State Forest boundaries. Note the location of the wetlands (red box and dots) numbered from left to right Old Boo, PW3 and PW1.*

3.3.3 The National Estate and conservation Areas

The conservation measures in the Pilliga began in 1968 and this increased gradually over time with the gazetting of the statuatory provisions. The Northwest Regional Assessment (RACAC, 2002; 2004) followed on from the federal govenments initiative which aimed to conserve a representation (15%) for each of the pre-European ecosystems (JANIS, 1997; Whipp, 2009). This saw a shift in governmental policy in NSW and other governments, where management objectives were spawned from environmental awareness and resulted in the preservation of heavily cleared and modified *Callitris-Eucalyptus* communities. In 2001, then Premier Bob Carr announced a moratorium on logging; and in 2005 protected 160,000 Ha from timber harvesting (BNCCAA, 2005; Forests NSW, 2008). The newly protected areas comprised the Pilliga and Timallallie National Parks, Pilliga Nature Reserve, and three State Conservation areas (Fig 3.4; OEH, 2014). A shift from active management to passive management has been a controversial issue with conservationists, farmers and forestry holding disparate views on how to manage the vegetation. The legacy of European land management activities may have caused a cascade of instability, changed vegetation structure and threaten the wetlands on the floodplain (Rolls, 1981; Norris et al., 1991; Whipp et al., 2009; Whipp et al., 2012).

3.3.4 Coal Seam Gas

The Surat and Gunnedah Basins have well known coal reserves and current petroleum exploration licence (PEL238) acquisition (PAL2) and production leases (PPL) exist to develop an area of 800,000 Ha into a major CSG field (Eco Logical, 2014). Santos energy has an active project in the Bohena area, which is approximately 98,000 Ha in the eastern Pilliga Forest and aims to meet 25-50% of NSW's natural gas requirements. A memorandum of understanding exists between the NSW government and Santos provides for the expansion of the number of wells, and connection of the CSG field to the Wilga Park power station for electricity generation. This requires the development of an extensive network of pipelines and water treatment facilities (Eco Logical, 2014). It is highly likely that by-products from the fracking process will pollute ground water, streams and soils (Milledge, 2012; Eco Logical; 2013). There have been reports and confirmation of spills causing aquifer contamination and vegetation dieback from the existing small scale pilot operations (NICE, 2012). With plans to expand and hasten the development of a CSG field in the area, it is concerning that the area is fire prone, and that the cumulative and long term impacts are relatively unknown. It is clear the scope and scale of such developments will result in the increased pressures on the GAB, degradation of conservation values of national significance despite stringent development controls and environmental management plans (NSW Government, 1997; Milledge, 2012).

3.4 Study sites

The study sites were selected based on the significant conservation value of the wetlands, their current ecological status, existing threats and management issues. Despite the history of catchment land-use, a cascade of instability may reduce their longevity on the floodplain. On that basis, this study provides a platform for science to inform management and guide policy. The following section will identify these sites and briefly discuss their importance and significance of this research.

3.4.1 Threatened Ecological Communities

Three wetlands were selected for this study: Old Boo (PW2); PW3 and PW1 (Fig 3.1; 3.4) are located in the northern section of the Pilliga National Park. They were accessed by forestry service tracks; Pilliga Forest Way and Old Coghill Road adjacent to the dog proof fence on the boundary of the park. The sites were selected as vegetation surveys previously undertaken in the area found a presumed extinct species: *Myriophyllum* *implicatum* (Orchard, 1985; OEH, 2015b), and identified them as a separate ecological community in the Pilliga (Benson et al., 2010; Hunter, 2010). Subsequent research by (Bell et al., 2012) mapped 340 wetlands, and noted two distinct types of lentic wetlands (tank gilgai and shallow basin), which did not conform to the standard types or categories (Keith, 2004). The authors also described the gilgai on the surfaces, yet dismissed their role in forming the wetlands but confirmed differences between more common lattice gilgai. It was suggested the water holding depressions may have formed along ancient drainage lines intersected by more recent streams, and that wet and dry phases (ENSO) were part of a maintenance cycle driven by overland flows and heavy rainfall. It was conceded little was known about the hydrologic regime or geomorphic processes and more research was required. The extent of their distribution was confined to be 121 Ha in an ellipse corridor (40 km by 8 km) stretching from the northern most section of the Pilliga Forest in a northwest direction toward the Namoi River. The majority of the wetlands surveyed were <1 Ha in size (92%), of which 233 (68.5%) fell on private land as opposed to 107 (31.5%) protected within the boundaries of the Pilliga National Park and State Conservation areas.

Additionally, 31 wetlands were examined with 240 plots recording the vegetation assemblage's composition and species richness in relation to water depth and wetland size. The surveys revealed 131 taxa formed three separate vegetation communities and wetland associations: a herb field in the shallow basins; a sedge land / herb field in the deeper tank gilgais, and a wet grass land. Three species listed under the Threatened Species Conservation Act 1995 were found, and six new taxa were recorded for the region. Surprisingly, it was discovered that these diverse communities were comprised mostly of native species, and were found within various habitats and niches of the wetlands. A reduction in species richness coincided with the dry phase and disturbance to seed banks from feral pigs, vehicles and sedimentation from forestry tracks may threaten the communities. Overall, the research enlightened about their confined distribution, uniqueness and the need to address threats in light of conserving, managing and improving understanding about such communities. This study was pivotal in the NSW Scientific Committees preliminary determination deemed the Pilliga Outwash Ephemeral Wetlands to be an endangered ecological community (NSWSC, 2014).

The purpose of this research is to expand upon existing knowledge by investigating their hydrologic history, what processes led to and maintain their formation, to document environmental changes as a response to management regimes, and to address the existing and potential threats to the wetlands longevity on the floodplain. This research incorporates the wetlands topography, sedimentology, geochemistry, geochronology and palaeoecology to fill knowledge gaps and to inform management. The results are outlined in Chapter 5.

4.0 Methods

4.1 Research strategy

The sampling was confined to three ephemeral wetlands in the Pilliga Outwash Province (Fig 3.1; 3.4). Additional investigation was conducted in the headwaters, mid and lower sections of the Coghill, Mollieroi and Goona Creek catchments in the adjoining Pilliga Sandstone Province of the BBS. The creek channels, bed, banks; the surrounding hillslopes, flood plain, vegetation structure and forestry tracks were examined. The sediment sampling at the wetlands, and catchment-wide exploration aimed to determine or inform the following:

1. Scientifically test the historical scenarios that altered fire regime and forest structure have led to a cascade of instability affecting the creeks, their floodplains and wetlands as purported by Rolls (1981);
2. Determine the stratigraphic boundaries, sedimentation rates and the age of the wetlands, specifically what is or was their characteristic hydrology, and the principle geomorphic processes that formed and maintained them;
3. Assess stream morphology at the catchment scale to understand flow thresholds and disturbance by investigating recent flow and fire activity; and to investigate linkages between streams and wetlands;
4. Identify sediment sources, storage and transport zones to deduce temporal and spatial shifts in sediment deposition and erosion;
5. Evaluate the current status of the wetlands, creeks, and floodplains; in the context of their history, trajectory of change, current threats and the implications for the wetlands longevity on the floodplain.

4.2 Study design and field sampling procedures

Three wetlands were selected for investigation based on a previous study (Bell et al., 2012) and examination of high resolution satellite imagery in Google Earth. The wetlands were chosen based on their size (being amongst the largest identifiable), identification of rare and endangered aquatic plant species (Bell et al., 2012) and ease of access.

Two field work campaigns were completed between 11th-15th February and 2nd-5th of July 2015. There was persistent surface water in Old Boo on both occasions. The other wetlands PW3 and PW1 had pools in the deepest depressions in July from the recent storm activity and above average rainfall in June. The surface of the wetlands was scanned for evidence of geomorphic processes and for past anthropogenic activity or disturbance from feral animals. Three continuous sediment cores were extracted at each wetland (n=9) using a steel corer with a 50 mm wide PVC liner, a post driver and two heavy duty jacks attached to the corer's collar by a chain (Appendix 4). Double jacking was required due to the difficulty of removing the core from the sediment. The coring sites radiated from the basin centre or the deepest depression, an intermediate site, and the margin of the basin. The location of each core was recorded with a hand held Garmin GPS with a typical accuracy of ± 4 metres horizontally and ±1 metre vertically.

4.2.1 Magnetic susceptibility and sub sampling procedures

Magnetic susceptibility measurements were made on the unopened cores. A Bartington Magnetic Susceptibility meter (MSI) and loop sensor was used to measure the cores' response to magnetic minerals haematite and magnetite. Each core (n=9) was measured at 5 cm intervals with blanks recorded at the start and finish. The initial results provided a guide for subsequent sub sampling.

The cores were opened in a darkened laboratory under a dim red light to protect the sediments to preserve samples for portable optical luminescence (pOSL) analysis. Half cores were kept wrapped in black plastic in dark conditions for pOSL analysis. Core descriptions were performed on the other half of the core documenting facies boundaries, grain size and colour (Munsell; 1975; Northcote, 1979). A photographic record for each core was also kept for future reference.

Old Boo wetland was selected for detailed investigation because it has a more consistent sedimentology and stratigraphy than either PW3 or PW1. Old Boo also appears to have more regular inflows and to hold water for longer periods than the other wetlands. Sub samples were taken in slices at 2 cm intervals (n=127) and then divided and processed for each methodology (Appendix 1). Simple proxy indicators were measured on the remaining cores from Pilliga wetlands 3 and 1 (sample code PW3 and PW1) (n=6) to derive catchment trends and distinguish local factors.

4.3 Topographical surveying

The perimeter of each wetland was traversed and waypoints were recorded with a Garmin handheld GPS. A Leica TC805 Total Station (TS) was used to perform a topographic survey of longitudinal and cross sections for each wetland (n=7). Tape and inclinometer surveys (n=9) were conducted in key areas along the Coghill, Goona and Mollieroi Creeks to capture the geomorphic processes occurring at the catchment scale. An assessment of creek lines and hill slopes was made to examine stream planform, channel morphology and geomorphic units. Detailed site descriptions also identified recent flood, flow and fire history, and evidence relating to erosion, aggradation, deposition and bioturbation.

All topographical surveying data was processed using standard techniques to map the study sites and to calculate the surface area of each wetland using ArcGIS 10.3 spatial imagery software. Further, in lieu of LIDAR topographic data, a digital elevation model (DEM) layer of the catchment was created using Enhanced Lee Smoothing of the 1 arc second SRTM national DEM (Yu and Acton, 2002). Generally, this technique removes the background noise from vegetation and coarse scale objects, but retains the finer scale details required for the DEM. A 6 x 6 cell was selected as the most suitable level of smoothing.

4.4 Sedimentology

4.4.1 Particle Size Analysis, Loss on Ignition and Carbonates

Particle Size Analysis (PSA) is an important soil characteristic and a technique applied to assist in interpreting sedimentation style and environmental reconstructions (Sperazza et al., 2004). The Particle Size Distribution (PSD) acts as a proxy and provides valuable information as to the current or past depositional environment and hydrologic regimes (Sperazza et al., 2004). In addition, grain morphology (size) influences entrainment and suspension which can reflect the energy of the systems and its flow regime (Cheetham et al., 2008). A Malvern Mastersizer 2000 with a HydroG dispersion unit (Malvern) was the primary method used for this research at Macquarie University.

The Malvern has a measurement range of 0.02 – 2000 µm, divided into 100 bins that cover the clay, silt and sand categories of the Wentworth (1922) size scale. Sediment is measured by laser diffraction, where the suspended particles pass through a laser beam and sensors record the angular distribution and the forward scatter. The Mie diffraction theory is utilised to convert the intensity of the scattered light to a grain size class and then particle size volume percentages for the samples (Sperazza, et al., 2004). Samples (n=142) were first oven dried at 60˚C, weighed and then dispersed in sodium Hexametaphosphate $(NaPO_3)_6$ and deionised water, as described by (Ryzak and Bieganowski, 2011). They were then placed in an end-over-end mixer for 24 hours and were wet sieved through a -0.5 phi (≈1.4 mm) mesh. While lower than the detection limit, experience has shown that the Malvern pumps do not perform well with particles larger than around 1.4 mm. The coarse sand (>1.40 mm) was also collected, dried and weighed.

The Malvern settings were set as follows: particle (1.544), water (1.33) refractive index, and a particle absorption coefficient of 1.0. The suspended sample was put through a four way sample splitter to reduce the sample size and a laser obscuration range between 10-15% could be obtained when added to the HydroG. Test runs were completed to find the best pump (1750) and stirrer (700) speeds, while ultra-sonic bursts ensured dispersal. The background was set to 20 seconds and 20,000 measurement snaps with a laser intensity <75%. Two measurement cycles of 30 seconds with 30,000 measurement snaps with 5 seconds delay were run on the primary and sub samples. The mean was taken of the four cycles.

Organic matter and carbonate content was determined for the Old Boo cores (1-3) at 2 cm intervals (n=125). The samples were oven dried at 105˚C weighed and then placed in a furnace at 550˚C for 4 hours (LOI) (Heiri et al. 2001). Following ignition the samples were transferred to a desiccator for 1 hour and then weighed (% LOI) (Fryirs et al., 2014). The process was repeated at 950˚C for 4 hours to give the (% $CaCO_3$) of the dry sample weight (Heiri et al. 2001).

4.5 Inorganic geochemistry

4.5.1 Energy Dispersive X-Ray Fluorescence Spectrometry (EDXRF)

X-Ray Fluorescence (XRF) spectrometry was used in this study for the geochemical inorganic analysis of sediments. It is a non-destructive technique that determines elemental compositions and measures their range of concentrations at the detection limits (100% to mg/kg) (Brouwer, 2010). X-ray fluorescence spectrometry is applied to a diverse range of matrices for various purposes in environmental science, archaeology and to quantify heavy metal contamination (Rouillon et al., 2013; Croudace and Rothwell, 2015; Davies et al., 2015). Quantitative XRF analyses involves irradiation of a sample by an X-ray beam and measuring the response by a detector (EDXRF). Each element has a known fluorescence signature which is released in X-ray photons when the energy is sufficient to remove the inner shell electrons from atoms in the sample (Rollinson, 1994; Brouwer, 2010). The intensity of the radiation released for each element is used to determine the concentration of and elemental compositions of the sample (Brouwer, 2010). EDXRF was used in this study because geochemical indicators and fluctuations of concentrations or elemental ratio (e.g. Ti/Rb) can be used as proxies to infer environmental change and conditions (Rollinson, 1994; Davies et al., 2015). The XRF instruments used were: an Olympus DELTA field portable EDXRF (pXRF), and a Cox Analytical ITRAX core scanner.

4.5.2 ITRAX

ITRAX is a high resolution EDXRF scanning system with a range of environmental applications (Croudace et al., 2006). It can provide magnetic susceptibility measurement, a radiograph and an optical image of a sediment core, and can perform scans at submillimetre intervals that detect fine-scale geochemical changes throughout the profile (Croudace et al., 2006). It’s a relatively new and developing analytical technique; however, it is increasingly used and suitable for analysing continuous sediment cores (Croudace and Rothwell, 2015). High resolution scanning allows sediments to be analysed in great detail that can’t be achieved via manual sampling using the Olympus Delta pXRF equipment. The broad purpose of the ITRAX scanning was to detect the elemental composition of the sediment, and to derive a suite of geochemical indicators which can be used to infer and identify environmental conditions. Calibration of ITRAX measurements against the pXRF data assists in determination of elemental ratios useful as environmental proxies for factors such as flood deposition, particle size fluctuations, and pedogenesis (Rollinson, 1994).

The ITRAX analysis was conducted at the Australian Nuclear Science and Technology Organisation (ANSTO). The cores from Old Boo wetland (n=3) totalling 2.39 metres were scanned at 1 mm intervals. Prior to scanning, the cores surface was cleaned with hand tools to remove any foreign materials, such as PVC plastic from core opening, and to ensure a smooth surface for optimal analysis. However, due to the sediment’s characteristics and low moisture, the cores had several cracks from previous processing. Subsequent destructive sampling techniques were performed on the core. To test the accuracy of the ITRAX scans estimations calibration with pXRF was undertaken by averaging roughly uniform sample intervals (20 mm) to convert the ITRAX counts per second (CPS) to concentrations (mg kg^{-1}). Linear regressions were derived for each element (Schillereff et al., 2015). Overall, the results varied between the elements suggesting that only some ITRAX element profiles can be used confidently (Appendix 2). Volume magnetic susceptibility (κ) scans were also completed at 5 mm intervals. The ITRAX results were averaged for comparisons to the volume MS measured using the Bartington MS1 at Macquarie University (50 mm). This allowed fine scale and broader scale changes in ferruginous characteristics to be captured.

4.5.3 Olympus Delta Field Portable (pXRF)

For this study, an Olympus DELTA pXRF 50 kV spectrometer was used at Macquarie University for *ex situ* analyses. This instrument was chosen because of its ability to produce accurate results when coupled with robust Quality Assurance and Quality Control (QAQC) procedures (West et al., 2014). Three cores from Old Boo were sampled at 2 cm intervals (n=125) and after drying each sample was sieved to <2 mm and then ground to a fine homogenous powder sample using an agate mortar and pestle. The standard 'soil' mode was selected and all three beams were set to analyse the sample for 45 secs per beam (135 secs total). A software calibration check was performed on a sterling silver disc each day prior to use. Two certified reference materials (CRMs) (NIST2710a; NIST2711a), and a blank (SiO_2) were also measured for 135 secs before and after use for QAQC purposes. The XRF sample cups were lightly packed with 8 g of dried sediment and lined with Chemplex 3.6 µm Mylar X-ray film base (Gore et al., 2007).

As part of the standard XRF procedures the measurements obtained from pXRF were subject to QAQC. They are used to ensure the validity of and to constrain the data produced. The precision and accuracy of the results were quantified by calculating the relative standard deviation (RSD) and the relative percent difference (RPD). Five CRMs (NIST2709a, NIST2710a, NIST2711a, CNRC BCSS-1 and CNRC PACS-2) were analysed 3 times for 135 seconds prior to analysis (n=125). The results for precision (RSD) and accuracy (RPD) for the pXRF, a comparison of the measured and target CRM elemental values, and recovery percentage for each element are summarised in Appendix 3 (Table 9.2-9.7). The mean RSD for each element are K (1.34), Ca (0.54), Ti (1.16), Mn (1.45), Fe (0.44) Rb (0.93), Sr (1.36) and Zr (0.88). The mean RPD for each element were K (10.51), Ca (3.44), Ti (8.72), Mn (4.5), Fe (10.90), Rb (2.75), Sr (21.31) and Zr (267.32). The QAQC for this study revealed that a decline in accuracy and precision coincides with low elemental concentrations. Therefore, the Olympus Delta pXRF is more accurate at analysing elements in high concentrations. The blank SiO_2 recorded 'not detected' (ND) for all background concentrations of elements analysed. Given the Pilliga Forest's history, low levels of elements associated with anthropogenic activities are expected whilst other major elemental concentrations recorded are sufficient for the purpose of this study.

4.5.4 Cluster and Principle Component Analysis

Cluster and Principle Component Analysis (PCA) was conducted at ANSTO from the three ITRAX profiles. The profiles were examined and elements were selected based on their down core variation with the assistance of Patricia Gadd. The data was then analysed using the codes written and modified by the R Studio team, Patricia Smith of Cambridge University and Claire Kain of UNSW and used in the statistical interpretation of the cores. This stratigraphic and bi plots provided an insight into the stratigraphy, its boundaries and changes that have occurred over time; and the dominant mode of elements, (detrital or pedogenic) in the wetlands which informed as to depositional history, catchment and anthropogenic influences captured by the geochemical signature.

4.6 Sediment geochronology

4.6.1 Portable Optically Stimulated Luminescence (pOSL)

Portable OSL investigates luminescence signals of feldspar and quartz grains in bulk clastic soils and sediments under different wavelengths of the electromagnetic spectrum (Muñoz-Salinas et al., 2011). The measurements and their intensities are used to form a profile which can be used to develop an understanding of stratigraphy and sediment characteristics (Burbidge et al., 2007; Sanderson and Murphy, 2010). Plotting the variations of intensity (photon counts) down the profile assists in approximating burial age (age range finders) of stratigraphic units, delineation of and detection of crypto stratigraphic boundaries and post depositional mixing of sediments (Sanderson and Murphy, 2010; Stang et al., 2012; Munyikwa et al., 2012). Shifts in geomorphic processes can also be inferred when considering the surrounding geology (source), mineral ratios (provenance) and fluvial processes (system conditions) (Muñoz-Salinas et al., 2014). Additionally, pOSL can assist with identifying a supplementary site in the sediment profile for more robust age determination of samples by OSL (Sanderson and Murphy, 2010; Bishop et al., 2011).

The pOSL analyses were conducted at Macquarie University using a reader developed by the Scottish Universities Environmental Research Centre (SUERC). Sampling was conducted under dark conditions with the aid of filtered red light to avoid bleaching and altering the luminescence signal. A small aluminium dowel (5 cm by 2 cm) was pressed firmly into the sediment at 5 cm intervals for the three wetlands (n=225). The samples were broken up and placed in a petri dish and then inserted into the reader for stimulation by infrared (IRSL) and blue (BLSL) light using the CW (7) sequence mode. The samples were stimulated by IRSL and BLSL for two 30 second cycles which was preceded and followed by 10 seconds of dark counts. The luminescence signal was counted by photo detectors and multipliers and expressed as terminal photon counts. The incorporation of pOSL is a novel approach for multi-proxy studies of semi-arid wetlands in Australia.

4.6.2 Accelerator Mass Spectropy: Radiocarbon (^{14}C)

Radiocarbon is a widely used chronological technique that is applied to fluvial, lacustrine and other sediments to infer timing of events and ages for sedimentary profiles (Chiverrell et al., 2011). Carbon has three isotopes: stable ^{12}C and ^{13}C, and unstable ^{14}C. Specifically, ^{14}C is produced by a series of reactions (neutron + $^{14}{}_{7}N \rightarrow$ $^{14}{}_{6}C$ + proton) in the atmosphere and environmental deposition occurs after an oxidising reaction expressed as ($^{14}CO \rightarrow$ $^{14}CO_2$) (Bronk Ramsey, 2008; Hua, 2009). It is stored in terrestrial and aquatic reservoirs and once it is fixed to organisms via photosynthesis or biotic uptake, radioactive decay begins. The decay continues at a constant rate defined by the isotopic half-life (5730 ± 40), which is independent of external inputs (Bronk Ramsey, 2008; Hua, 2009).

The ANTARES FN accelerator mass spectrometry (AMS) facilities at ANSTO were utilised for the purpose of this study. The sampling was guided by core descriptions, magnetic susceptibility, ITRAX and LOI results to capture the age of the wetland sediment facies. The low organic content of the sediments and low concentration of macroscopic charcoal meant that radiocarbon analysis would be performed on 'bulk organics' within the sediment. The samples (n=6) were taken in 5 cm slices from three cores from Old Boo (1-3) at the upper and lower boundaries of the wetland facies (25-35 and 40–55 cm) to capture the onset of wetland conditions, and to extrapolate sedimentation rates. The pre-treatment Acid-Base-Acid (ABA) included the removal of roots and rootlets; 2M HCl at 60˚C for 2 hours to remove carbonate contamination; dilute NaOH (0.5 %) at room temperature for 3 hours to remove humic acid contaminants; and 2M HCl at room temperature for 2 hours before the standard treatment for sediments (Fink et al., 2004).

The AMS technique counts the ^{14}C atoms relative to the ratio of stable (^{12}C ^{13}C) isotopes by fractionation post CO_2 and graphite conversion of the sample (Wood, 2015). AMS is suitable for sediments with low organic material (such as ephemeral wetlands), and can reveal reliable responses from sample with less than 1 mg of Carbon (Wood, 2015). The variable production rate of ^{14}C in the atmosphere in the past necessitates a calibration tool to convert radiocarbon ages to calendar ages. For this purpose conventional radiocarbon ages were calibrated using the southern hemisphere calibration data set SHCal13 (Hogg et al., 2013) and the OxCal 4.2 calibration program (Bronk Ramsey, 2009). No reservoir correction was made because the water bodies are small, ephemeral and fed by surface runoff not groundwater.

Despite the limitations of radiocarbon dating (such as reservoir effect) it is a reliable technique for dating the late Holocene (the focus of this study) and is also a key element for enhancing the understanding of the environmental history of the Pilliga Forest. Therefore, the ^{14}Carbon (^{14}C) isotope is the primary method of analyses used in this research for age determination, constraining the onset of wetland conditions from bulk sediments (Chiverrell et al., 2011; Wood, 2015). Age depth plots were constructed from the mid-point (i.e. 22.5; 42.5 and 47.5 cm) for each sample to derive numerical ages and to calculate sedimentation rates. These rates calculated (median age/depth interval) gave the radiocarbon sedimentation rate (cm/year).

4.6.3 Excess ^{210}Pb

Excess ^{210}Pb ($^{210}Pb_{ex}$ or unsupported ^{210}Pb) is a geochronological technique based on the difference between total and supported ^{210}Pb. Supported ^{210}Pb is formed *in situ* by the radioactive decay of uranium-238 and its daughter isotopes (radium-226, ^{226}Ra; and radon-222, ^{222}Rn). Disequilibrium between ^{226}Ra and ^{210}Pb occurs due to the release of ^{222}Rn gas into the atmosphere, where it decays to ^{210}Pb that is deposited by atmospheric fallout on the Earth's surface. Therefore, total ^{210}Pb in sediment has two components: supported ^{210}Pb derived from *in situ* ^{226}Ra decay and assumed to be in equilibrium with the ^{238}U decay series, and excess ^{210}Pb

derived from atmospheric fallout that is in disequilibrium with ^{226}Ra (Appleby, 2001). Excess ^{210}Pb cannot be measured directly, so it is determined by subtracting supported ^{210}Pb activity (determined by measuring ^{226}Ra) from total ^{210}Pb activity (determined by measuring ^{210}Pb or its daughter isotope polonium-210; ^{210}Po).

Age-depth models can be derived from excess ^{210}Pb profiles in sediment and these can be used to determine sedimentation rates and to establish excess ^{210}Pb chronologies (Appleby, 2001). Two models are often used: the constant initial concentration (CIC) model which assumes that the supply of excess ^{210}Pb with constant initial concentration varies in proportion to the mean sedimentation rate (e.g. in systems dominated by excess ^{210}Pb supply from the catchment), and the constant rate of supply (CRS) model which assumes a constant rate of excess ^{210}Pb supply related to constant atmospheric flux, and allows for changes in the initial excess ^{210}Pb concentration in sediment due to variable sedimentation rates (e.g. in systems dominated by supply of excess ^{210}Pb from the atmosphere).

Dry bulk density and moisture content were measured (n=10) (Appendix 9 Table 9.14), before they were wet sieved at <63um to remove sand, ground to a fine powder and redried at <60˚C to avoid volatisation (n=10). Further preparation and processing followed standard procedures at ANSTO (Atahan *et al*., 2014). Alpha spectrometry was used in this study due to a limited supply of sediment and expected low concentrations of radioisotopes. This technique is often applied in studies of the recent past and is most suitable for timescales up to 200 years, and is particularly relevant when constructing sediment accretion rates from the impacts of European land management (Wallbrink and Murray, 1993; Gale et al., 1995; Gell et al., 2005; Appleby, 2008). Therefore, it is a suitable technique for use in this project.

4.7 Palaeoecology

The sediment from Old Boo core 1 was gently disaggregated with an agar mortar and pestle to avoid destruction of macrofossils before being examined under a Leica DM2500 compound microscope (100 to 400x) magnification by Dr Tsuyoshi Kobayashi at Office of Environment and Heritage (n=46). Observations recorded the presence and absence of aquatic plants and animals. Microphotographs were taken for identification.

5.0 Results

5.1 Catchment topography

The study area catchment is in the northern section of the Pilliga Forest as shown by the digital elevation model (DEM) (Fig 5.1). The main contributions to stream flows come from the Coghill, Goona and Mollieroi creeks which join into Coghill Creek to form an ephemeral dendritic drainage system leading to the Namoi River. Each creek begins in the Pilliga Sandstone province of the BBS (Morgan and Terrey, 1992). The highest elevation in the catchment is 330 m ASL. The creeks flow in a southeast to northwest direction, influenced by the dip in the underlying geology, into the Pilliga Outwash province (Hesse, 2000). The outwash is an alluvial plain and, although the Pilliga Sandstone province has low relief, the Pilliga Outwash province has considerably lower relief. Flows in these creeks are activated by significant rainfall. Rainfall received in June 2015 was 45.2 mm, close to the monthly mean of 48.5 mm (BOM, 2015a), but failed to produce flow in the creeks observed, although in some cases runoff from the banks had flowed onto the dry channel bed.

The wetlands are located in topographic lows toward the margin of the two provinces and their boundaries are shown, labelled from west to east, Old Boo, PW3 and PW1 (Fig 5.1). Their position suggests they were part of much older water courses that are no longer capable of transmitting flows presumably due to lower runoff (Bell et al., 2012). The wetlands are disconnected from the stream network. PW3 and PW1 are completely disconnected from Goona and Mollieroi creeks, while Old Boo maintains an overflow connection to Coghill Creek.

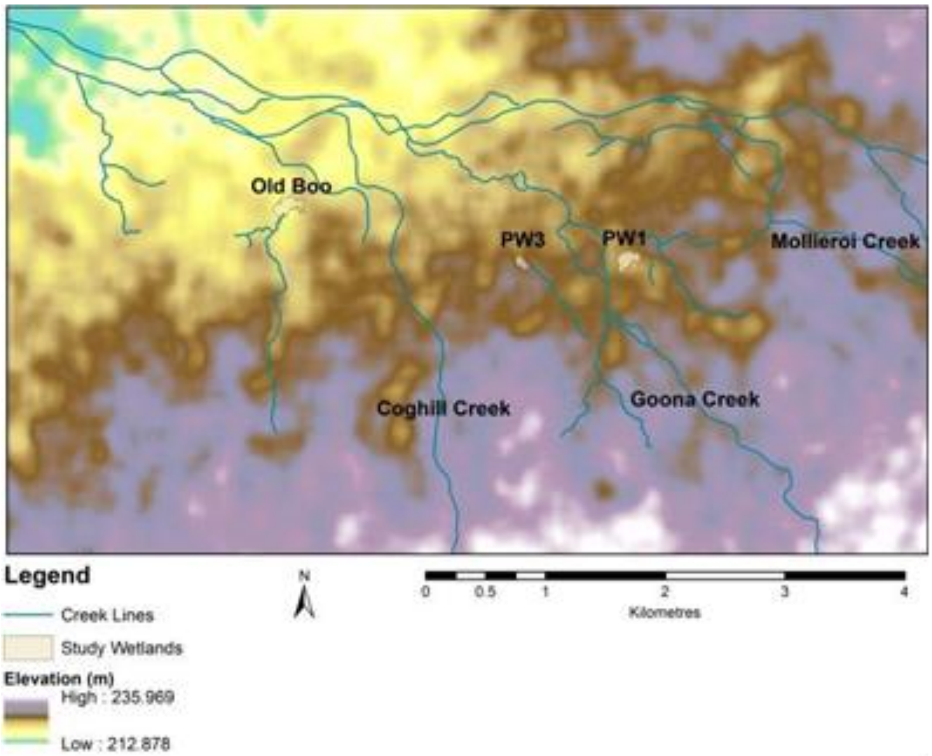

***Figure 5.1**: A 6 x 6 cell Enhanced Lee smoothed 1 arc second SRTM Digital Elevation Model of the study area. The three wetlands from left to right Old Boo, PW3, PW1, and the major streamlines Coghill, Goona and Mollieroi leading to the wetlands are shown in blue. A more detailed overview of the streams can be found in Fig 5.7. All the wetlands occur in very gentle topographic lows or at the margin of the alluvial plain (roughly the area shaded yellow). Note that the DEM contains artefacts relating to the tree canopy topography which affects its accuracy and prevents accurate mapping of the catchment area.*

All the wetlands are fed by local inflows to some degree although only Old Boo has a recognisable streamflow input from an area of low bedrock hills immediately to the south. Water persists in Old Boo for longer periods whilst the observations show the other wetlands are reliant on sporadic surface runoff within their local catchment for inflows. There is a possibility that the wetlands receive overbank flows from nearby creeks during significant storms and flood events.

5.2 Wetland topography

At the time of first survey (February 2015) there was no surface water in PW3 and PW1 and little evidence of persistent soil moisture. Old Boo had shallow pools restricted to the Eastern end of the wetland. At the time of the second survey (July 2015) there was no surface water in the creeks. Shallow bodies of water remained in the deepest parts of each wetland, particularly Old Boo, where water levels and surface area inundation had increased toward the eastern end. During the recent storms in June 2015, 27.6 mm of 45.2 mm mean monthly rain fell on the 17th (BOM, 2015a). This storm event demonstrated the minimum water required for stream activation, flow thresholds and how sediment was being transported into and throughout the catchment. There were indications of local runoff into the wetlands (litter, pools) but depressions not directly connected to the surrounding catchment or shelving margins of the basins were dry and several gilgai in the wetland beds were also dry.

5.2.1 Aerial, GIS and GPS reconnaissance

Handheld GPS survey revealed that the basin shape of the three wetlands was similar; a kidney-like shape with a sweeping crescent on the northwest side, two lobes on the other and a narrower section in the middle that drained toward the depocentre. The smooth northwestern boundary is suggestive of a wave-formed shoreline, formed by southeasterly winds (Bowler, 1986). Easterly winds currently dominate during summer, the season of dominant precipitation. Beaches were observed with large gently sloped sandy banks with evidence indicating wave action, sorting of sediment and the dominant wind direction. The basin surfaces were undulating, with small rises and depressions. Gilgai were present on each wetland possibly formed by water perched above the impermeable fragipan in the subsoil. The gilgai were circular in shape, distributed toward the margins at Old Boo, no clear pattern at PW3 and the lower sections at PW1. They were bordered by small rises giving them a crater like appearance. The wetland boundaries were well forested by *Casuarina*, *Eucalyptus* and *Callitris*.

Coghill creek runs reasonably close to Old Boo in the southeast; although the other wetlands were completely disconnected, and had been for some time. A sandstone hillslope to the south and west of Old Boo was observed, with a chain-of-ponds stream following a drainage line into Old Boo (right of the photograph) (Fig 5.2). Several of the larger ponds in the more confined upper drainage line had water in them in February and July 2015. These had a buffer of *Lomandra* which formed a barrier to sediment entering the ponds from the drainage lines and hillslopes. No clear evidence of bedrock out crops was observed for PW1. There was a noticeable bedrock hill to the south of PW3 (Fig 5.3). There was evidence of recent anthropogenic disturbance from recreational vehicles on PW1 (Fig 5.4). The forestry tracks ran close to the margin of Old Boo and PW1, and the loose sandy surface may be a sediment source when entrained in surface runoff. PW3 was set back from the track and had a vegetated barrier separating the wetland from the road. Damage to the surface from foraging and wallowing feral pigs was clear. A pig trap was noted at PW1 and many skeletons were seen. No evidence of recent fires was noted.

***Figure 5.2**: An aerial photograph of Old Boo taken from the Phantom II drone. The view is looking to the east. The deepest basin is to the lower left (partly shaded) and the stream draining bedrock hills to the south is seen entering in the lower right.*

***Figure 5.3**: An aerial photograph PW3 showing the shallow water bodies and recent inputs of moisture have encouraged plant growth. The view is to the west. The smaller left-hand pond is within a gilgai depression adjacent to two more dry, but deep, gilgai.*

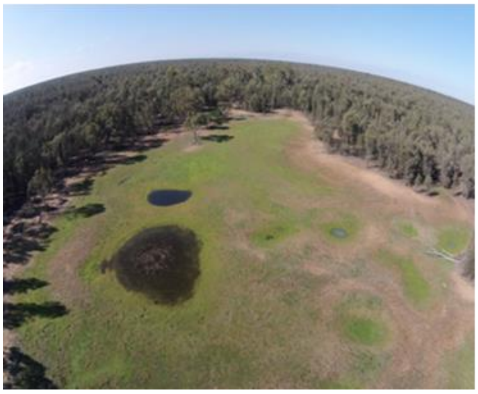

***Figure 5.4**: An aerial photograph of PW1 showing the shallow water bodies and recent inputs of moisture have encouraged plant growth. The view is to the west. Note the gilgai depressions (some filled with water) in the bed of the wetland.*

5.2.2 Topographic surveys and Automatic Level transects

Closer investigation of the wetlands topography was conducted using handheld GPS to map the wetland margins and total station survey of topographic transects (Fig 5.5; 5.6; Table 5.1). Despite the size differences, the wetlands share similar topographic characteristics. There is a bedrock hill to the south and west of Old Boo. There was evidence of runoff from the hillslopes and gullying along the creek. There is a possibility that overbank flows may come from the northeast. This flow direction crosses directly over the nearby forestry road from the adjoining floodplain. A small out cropping of bedrock was identified on the southwestern side of PW3.

No bedrock outcrops or hillslopes were observed in the PW1, but the largest input to wetland inflow may come from Mollieroi Creek in the northeast. Small gravels were present on the surfaces of all the wetlands which may have been transported across the floodplain during floods. Waters would need to be over 1.18 m deep in the lower section of Coghill Creek (Fig 5.8A5) to generate overbank flows, and would have to travel several hundred metres overland across the floodplain to reach the wetlands.

The runoff generated by rainfall is channelled to the deeper depressions and gilgai on each wetlands surface. The dimensions of and surface area for each wetland (Table 5.1) shows Old Boo is the largest and water may persist longer due to stream inflows. The core and transect locations are displayed in (Fig 5.5), and the topographic profiles provide detailed information as to the structure and features for each of the wetlands along the transect (Fig 5.6).

***Table 5.1**: Wetland topography and dimension summary table*

Wetland	Maximum Length (m)	Maximum Width (m)	Maximum Water Depth (m)	Surface Area (m^2)
Old Boo	375.96	215.61	1.40	29107.5
PW3	188.93	174.56	1.05	9207.35
PW1	264.54	222.05	1.25	22478.4

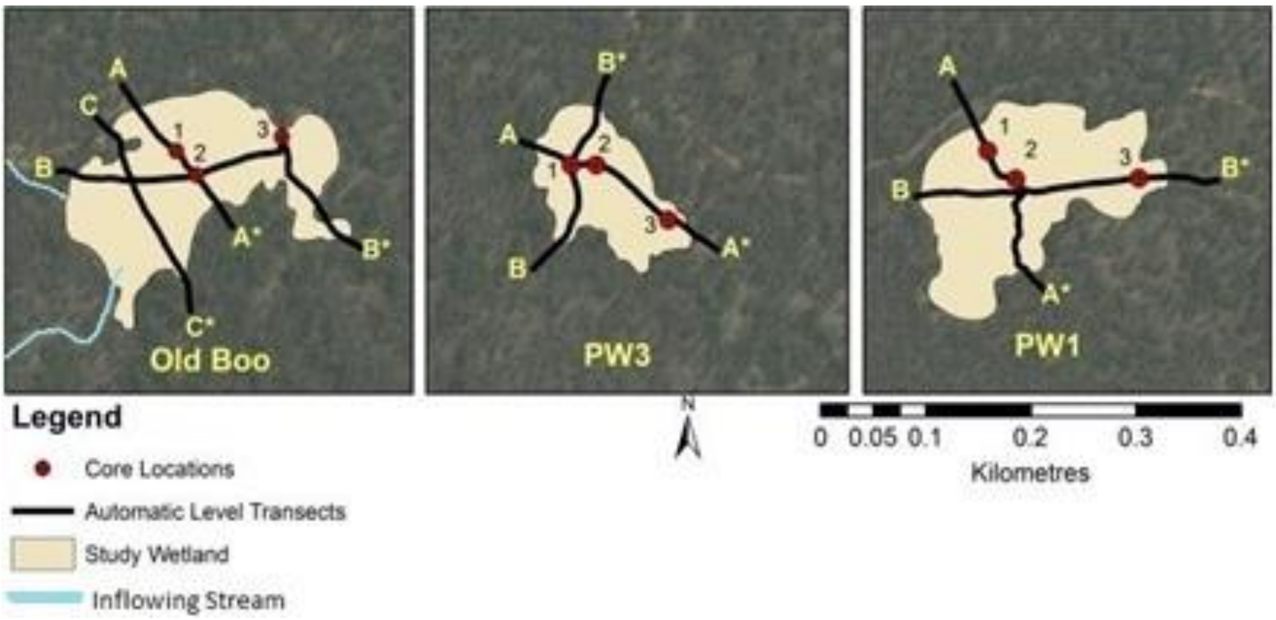

***Figure 5.5:** The wetland boundaries, and the start (ABC) and end (A*; B*; C*) positions of the automatic level transect are shown. The continuous core and GPS locations are marked (1-3). The GPS coordinates of the wetlands are: Old Boo (30.50308ºS 149.34148ºE), PW3 (30.50716ºS 149.36195ºE) and PW1 (30.50666ºS 149.37107ºE). The approximate location of the inflowing stream at Old Boo, is shown in blue entering from the southwest and draining bedrock hills from the northwest as shown above (Fig 5.2) and observed in the field. Note that the transects at Old Boo (A; C) and PW1 (A) cross over adjacent forestry service tracks/roads clearly shown at the northern boundary.*

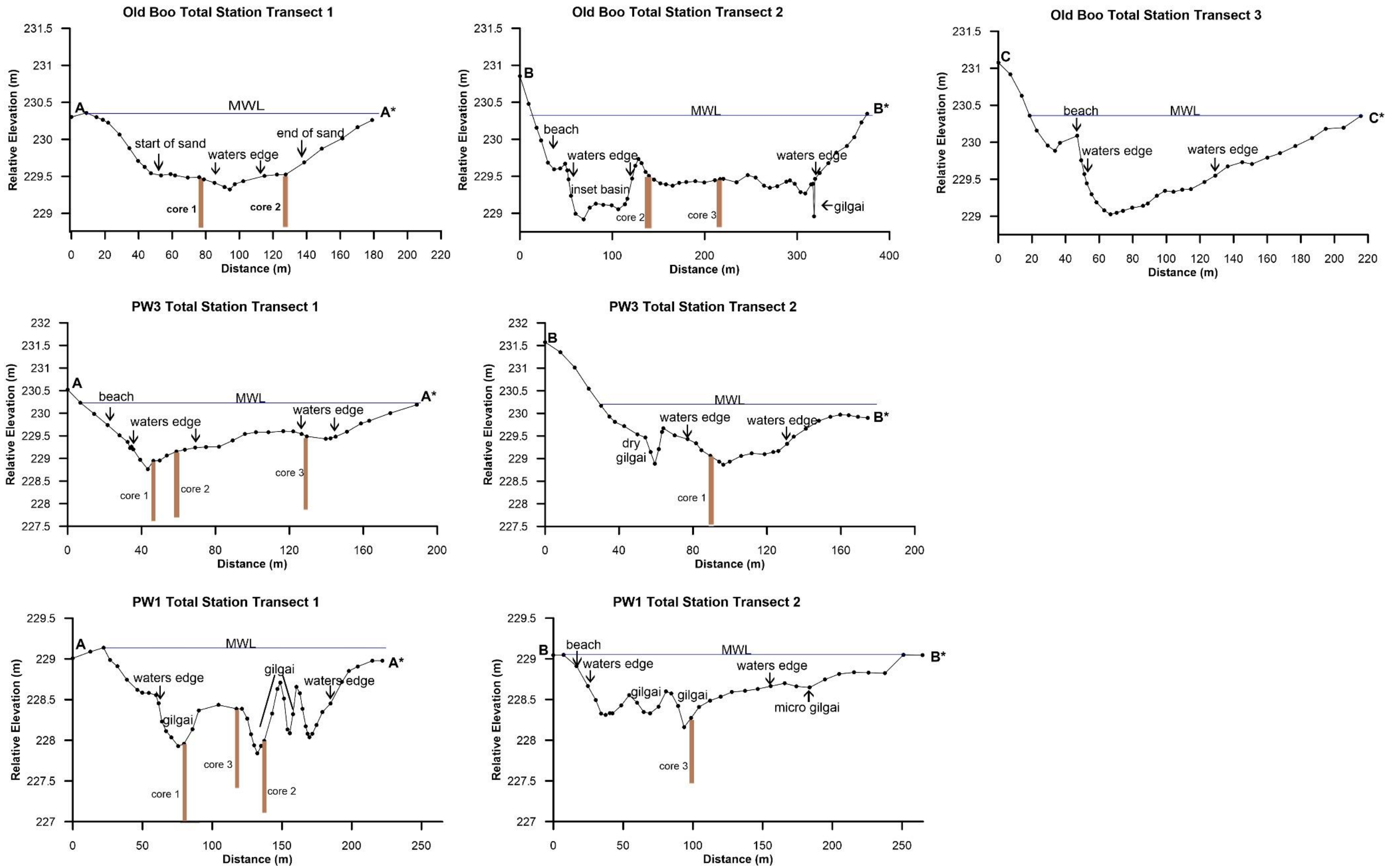

Figure 5.6: *The automatic level transects survey results with labelled features for each wetland. The maximum water level (MWL) is marked by the blue horizontal line. The maximum depth was measured from the lowest point on the margin (overflow level) to lowest gilgai or depression. The waters' edge at the time of the surveys in July 2015 is shown. Core locations and their relative depths are also marked in brown.*

5.3 Geomorphic adjustments in stream channels

5.3.1 Surrounding catchments

Tape and inclinometer surveys (n=9) were made to determine the downstream changes in channel morphology in the catchment. The catchment runs through an operational commercial forest, into the Pilliga National Park before crossing free hold lands (Fig 5.7) downstream of the wetlands. The surveys of Coghill Creek were undertaken in the upper to lower catchment (1-5); for Goona (1-3) and Mollieroi (1) surveys were taken in the mid catchment at points dictated by access tracks. The top of bank (TOB), channel width and height plus other geomorphic units are shown (Fig 5.8). The results revealed distinct changes and disturbance, located the sediment source, sink / accommodation areas and transport zones in the catchments. The fresh erosion at the Goona (2) knickpoint, bed scouring at Coghill (5), slight gullying at Old Boo and Goona (1-3), and signs of bank erosion suggest the creeks have undergone some modern change. The most compelling evidence was the wide sandy beds of the creeks in the lower Coghill (3-5) and at Mollieroi (1) (Fig 5.9). However, with only anecdotal evidence and no baseline data existing as to the creeks' natural (pre-European) state it is not possible to confirm or prove that catastrophic change has occurred following European settlement.

The hillslopes in Coghill (1-2) and Goona (1-3) had been recently burnt, and there were large bare patches of floodplain with a sandy sediment source (Fig 5.10A). The vegetation communities in the riparian zone were affected, with the more fire tolerant and resilient species (*Eucalypts*) showing signs of recovery at Goona (1-3). Fallen branches and logs were being covered by vertical sediment aggradation in the channels in all surveys (Fig 5.10B).

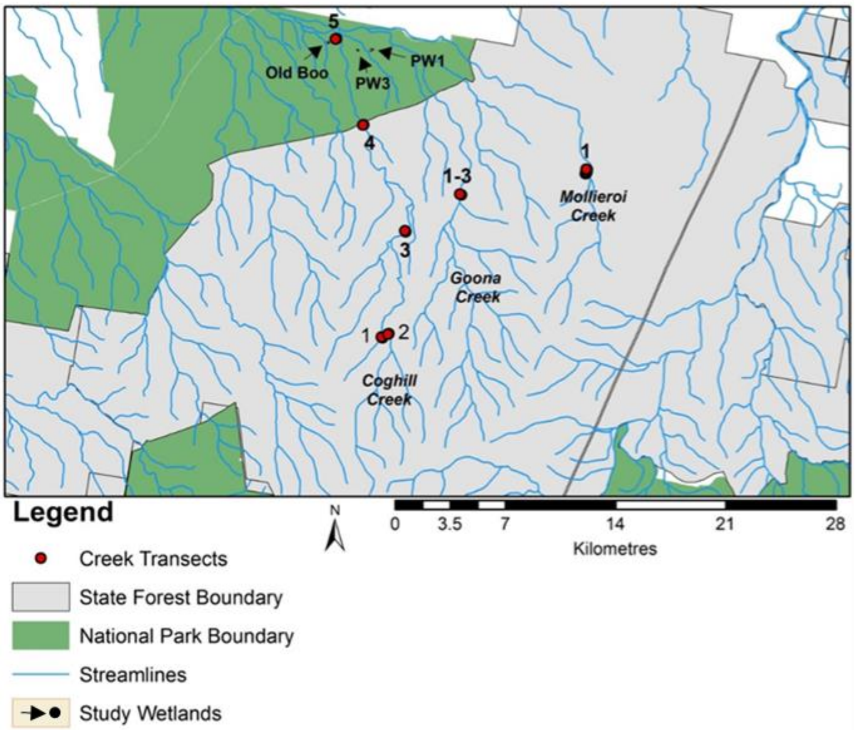

***Figure 5.7**: The tape and inclinometer survey locations for each creek in the catchment. Note the Coghill Creek surveys (1-2) are on two separate arms; and the three Goona Creek surveys, shown here by one red marker, were within 100 metres of each other above and below a small knickpoint.*

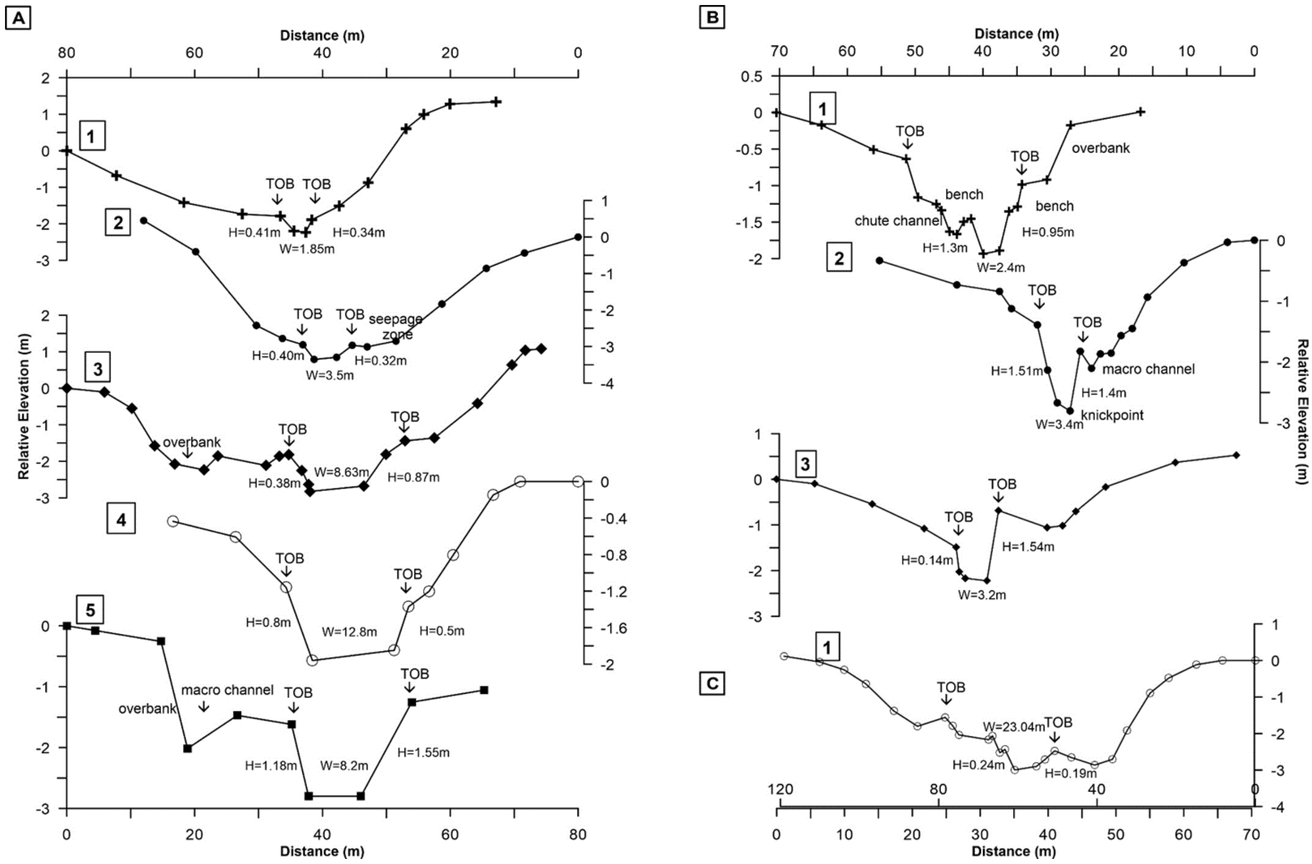

__Figure 5.8:__ The creek cross sections show __(A)__ Coghill from the upper (1-2) mid (3) to lower (4-5) catchment; __(B)__ Goona (1-3), above, 5 m downstream of, and below a small knickpoint, and __(C)__ Mollieroi (1) surveys are in the mid catchment. The widest channels were found in the lower Coghill (8.63 m) and mid Mollieroi (23.04 m). The channel was covered with loose sand, indicating sedimentation has occurred recently.

__Figure 5.9:__ The channel of Coghill Creek (4-5) looking down stream toward the boundary of Pilliga National Park. Low bank heights demonstrate the maximum water level needed for overbank deposition.

There was also evidence of additional sediment inputs from forestry service tracks that intersected creeks, where rill erosion on the shoulders provided a conduit for entrained and suspended sediment into Coghill (1-2) and Goona (Fig 5.10C; D). There was evidence of channel incision and deepening in the reach surveyed at Goona and Mollieroi Creek. There was slight bed and bank erosion at Goona with exposed bedrock at (1); a small knickpoint and undercutting which exposed tree roots at (2), and benches storing sediment (1 and 3) (Fig 5.10E). Scouring of the bed that exposed tree roots was seen at Coghill (5) (Fig 5.10F).

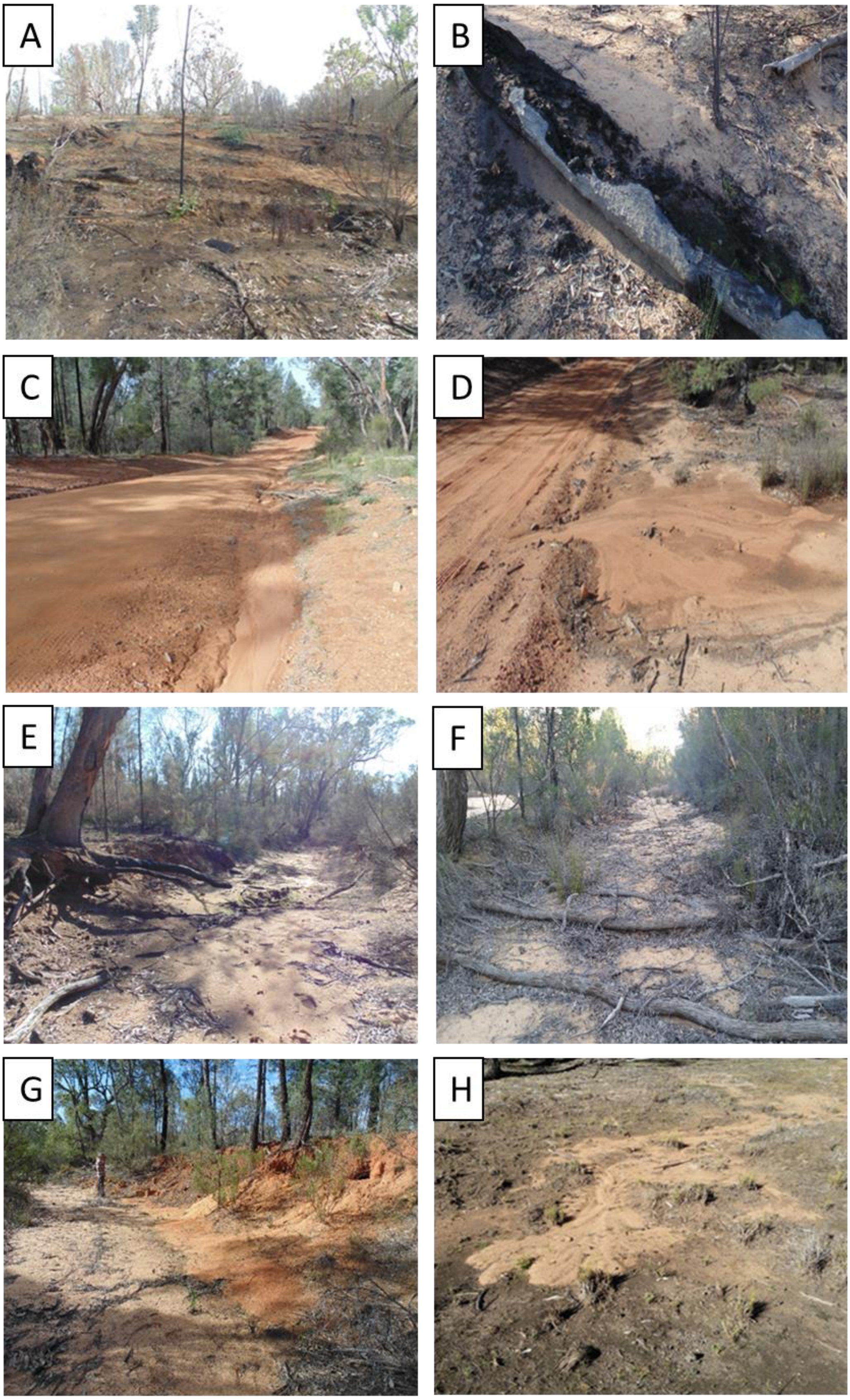

***Figure 5.10**: The changes observed in the Coghill, Goona and Mollieroi Creeks: **(A)** the hillslopes of Coghill (1) burnt during a recent fire; **(B)** in channel aggradation of sand covers burnt branches at Coghill (5); **(C)** sediment input from forestry roads flowing down into Coghill (1-2) at the crossing (top centre) and Goona **(D)**; **(E)** undercutting of the banks and exposed tree roots above the nick point at Goona (2-3); (**F**) scouring at Coghill (5); (**G**) bank erosion and fresh sandy sediment input from the floodplain at Mollieroi (1), and **(H)** sediment flux from the hillslopes at Old Boo as a result of the recent storms.*

The hillslopes were identified as a primary source of sediment generated by fires, and this was accommodated on the floodplain, within the channel and benches until downstream transportation. However, surface runoff from the recent storms appeared to have had minimal effect in transporting the sediment from the bare or vegetated hillslope into the channel and downstream (Coghill 1-5; Goona 1-3). At Mollieroi (1) surface run off had transported sand from the floodplain into the channel (Fig 5.10G). This suggests that rainfall in excess of 50 mm is needed to surpass the flow threshold and activate the flashy flow regime. If there is an efficient geomorphic (channel) connection with the catchments, the wetlands could be threatened by increased sedimentation. The main threat drawn from the catchment investigation was that a catastrophic fire followed by a high magnitude storm could potentially cause a sediment flux into the wetlands. Fresh sandy over bank deposits were seen (Coghill 4), but surface soil colour (grey adjacent to the channel, red further away) hinted that it was some time since the last overbank flow onto the floodplain which bordered the wetlands near Coghill 5. Additional observations of the local catchment bordering Old Boo showed small puddles of water but the extent of sediment transported from hillslopes during the recent storms was insufficient to reach the wetland (Fig 5.10H). However, a clear route and understanding of the systems processes was gleaned to inform a conceptual model of catchment and wetland changes.

5.4 Sedimentology

5.4.1 Core descriptions and sediment characteristics

The coring from the three wetlands had a combined length of 11.02 m, and the length of cores 1-3 at Old Boo including the cutting shoe were 95, 80 and 80 cm respectively (Appendix 4). Initial core descriptions were supported by the ITRAX optical and x-ray images (Fig 5.11A). The x-ray shows the down core variations in soil bulk density with a change in sediments identified by darker or lighter shades. Three distinct sedimentary units were tentatively identified in each profile. The boundaries for the wetland and floodplain facies, and the fluvial basal unit are: Core 1 (0-40 cm; 40-75 cm; 75-95 cm), Core 2 (0-35 cm; 35-65 cm; 65-80 cm), and Core 3 (0-37 cm; 37-69 cm; 69-80 cm). There were no laminations but a general trend of fining-up from a larger calibre of coarse sand of the basal unit was observed in the cores from Old Boo (Fig 5.11A), and those from PW3 and PW1.

The colour of the profiles generally changed at the facies boundaries. From the surface to the wetland boundary they were all a light brown grey (7.5YR 7/1) to brownish grey (7.5YR 5/1). The darker brownish grey colour (5YR 4/1) highlighted a change to the floodplain facies with an increasing clay and moisture content with depth; and a light or grey orange (7.5YR 7/4; 7.5YR 6/4) colour was indicative of the basal unit. Old Boo core 1 had a thin black brown (7.5YR 3/1) band at 40 cm, which was darker than the other cores, suggesting a shift from floodplain to wetland conditions at and above this zone. Stratigraphic units were later identified using the combined assessment of ITRAX scans, sedimentological properties, and correlating the observations between cores (Fig 5.11 A-E), by looking for intervals with the most change in all properties.

Preliminary coarse volume magnetic susceptibility (MS) (κ) measurements showed fluctuations indicative of a change of materials and a unit boundary. The higher resolution ITRAX κ measurements improved these results by showing finer scale variability between cores and wetlands. The general trends for each core were that: core 1 has an undulating pattern with six small humps at roughly every 15 cm, with the largest at 65-75 cm. Peak κ is at 45 cm and a second peak occurs at 85 cm. Core 2 displays a gradual increase until the peak κ at 40 cm, and a bulge around 35-48 cm followed by fluctuations to the end of the profile. Core 3 has slight variations from 0-25 cm where κ becomes stable until 35 cm, followed by a peak κ at 60 cm, and a fluctuating pattern until the cores end. Despite clear peaks suggesting changes in the profiles, there are inconsistencies and only a weak correlation of the stratigraphy can be made from this data alone. The moisture, organics (LOI) and carbonates ($CaCO_3$) profiles were only measured for cores 1-3 at Old Boo. There is a distinct increase in moisture (%) starting at 40, 35 and 35 cm respectively. The moisture (%) peaks between 50 and 60 cm in the more dense sediments, and then decreases down toward the sandy basal unit. The LOI profile also displayed similar trends amongst cores with two peaks in organics (%) around 20 and 40 cm, and a bulge corresponding with the floodplain facies. However there was variability in all cores for the top 40 cm. The $CaCO_3$ (% dry weight), Ca and Sr (counts per second) from the ITRAX scans all display similar trends with an increase in leached pedogenic carbonate in the subsoils from 35 cm in depth. Core 2 has a large bulge from 50-70 cm, and there's a small peak in core 1 at 10 cm deep.

5.4.2 Particle Size Distribution

The PSD results for Old Boo revealed a similar pattern of fining and coarsening throughout the profile (Fig 5.12). For the detailed record (Fig 5.12A) there is a clear trend within the sand, silt, clay and very coarse sand, and cores 2 and 3 (Fig 5.12B;C) are generally consistent with core 1. Trends of alternating fining and coarsening cycles are evident with changes in silt and sand (%). At 2, 4, 18, 26, 46, and 82-90 cm sand comprises 40-50(%) of the sediment in core 1. Between these peaks in sand content, silt is 50% or above at 6-20, 34-46, 46-82 cm.

5.5 Sediment Geochemistry

5.5.1 Principal Component Analyses

The PCA of selected elements from the ITRAX analysis show that there are two distinct groups of elements (Fig 5.13). These two groups, detrital (Si; Ti; Zr) and pedogenic (Al; K; Ca; Mn; Fe) are evident in the clustering of samples in the PCA bi plot. This statistical analysis expresses the main principal components as Score 1 and 2; here they are given for Old Boo core 1, 2 and 3 respectively (36.98% & 19.80%) 36.01% & 20.66%; 32.92% & 20.36%) (Fig 5.13; Appendix 5). The scores show that the pedogenically-mobile elements are the primary components of the elemental compositions for the wetlands. The detrital elements coming from--

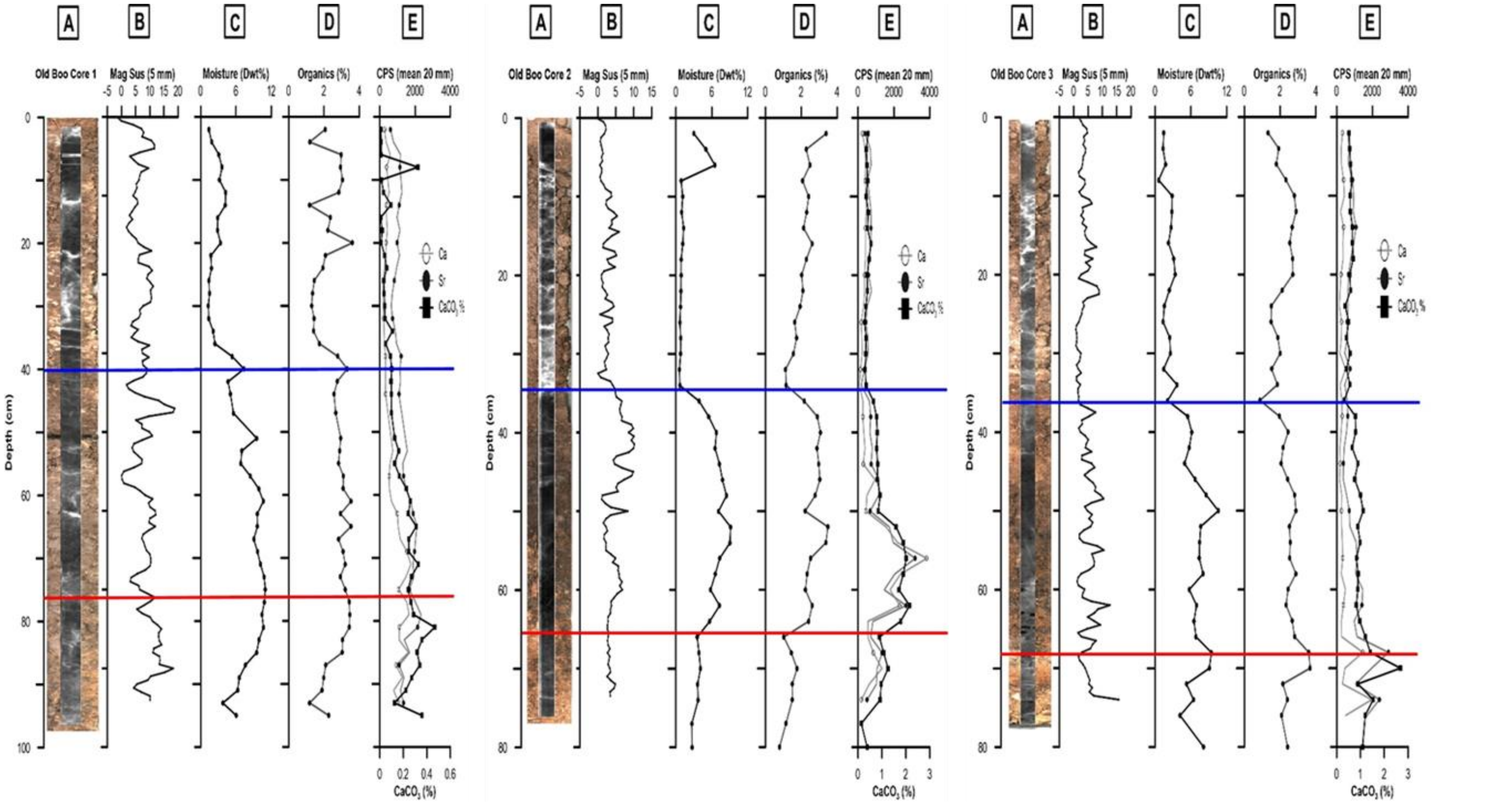

Figure 5.11: *Comparison of sedimentology from Old Boo cores 1-3 for (**A**) Optical image and Radiograph; **(B)** Magnetic Susceptibility; **(C)** Moisture content; **(D**) Organics %, and **(E)** Carbonates %, and ITRAX Ca and Sr profiles in CPS. The blue and red horizontal lines show the units boundaries for each core tentatively identified from preliminary analysis. Note that the cutting shoe is not included in the ITRAX scan which adds 3-4 cm in length to each core. A join occurs at 51 cm in core 1 as shown by a thin black horizontal line, but cores 2 and 3 are complete with no joins.*

outside the catchment, and not susceptible to alteration by weathering or redox, were found to explain less of the geochemical variations in the cores. These results suggest that pedogenesis has strongly altered these sediments, especially at depth.

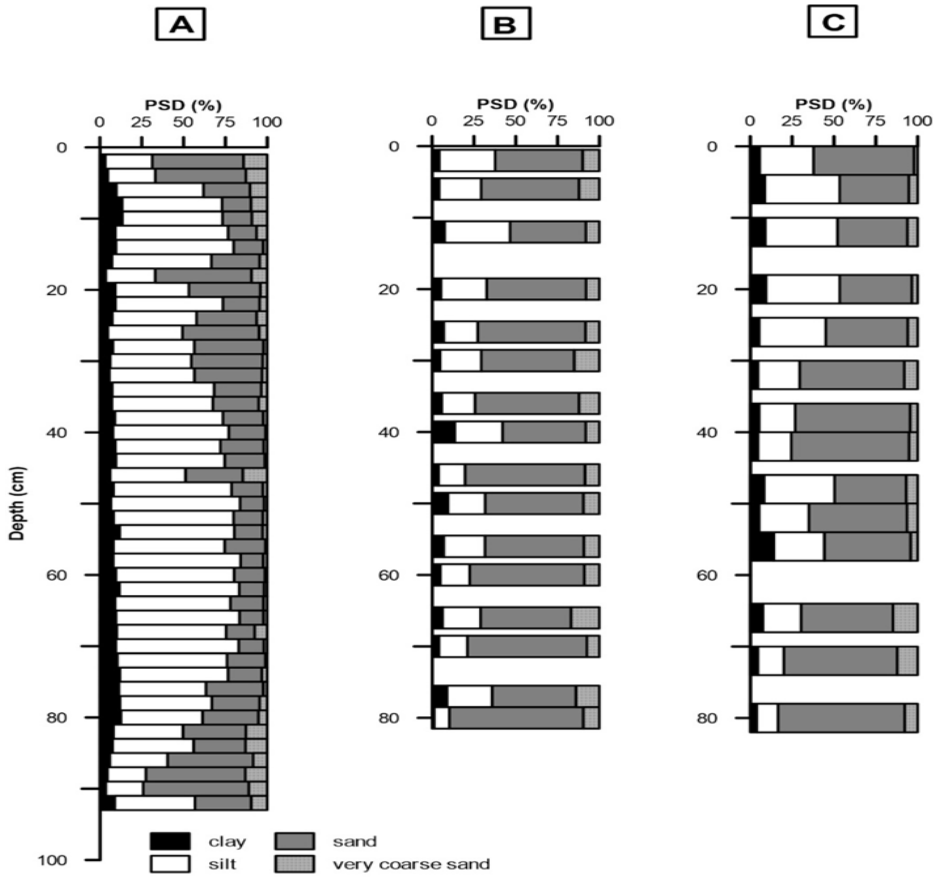

Figure 5.12: *The particle size distribution for Old Boo wetland with a detailed (2 cm interval) record for (**A**) core 1 (n=46); and selected depths for (**B**) core 2 (n=16); and (**C**) core 3 (n=14) to capture down profile variations.*

5.5.2 Elemental compositions and Cluster Analysis

The Olympus Delta pXRF and the Cox Analytical ITRAX core scanner recorded 38 and 27 different elements in the profiles measured from Old Boo (Appendix 3 Table 9.1). However, Aluminium (Al) and Silica (Si) were absent from the pXRF data set due to instrument configuration and choice of bulb. There is a join in core 1 at 45 cm shown by the gap in the profile (Fig 5.14). The plots show the elements of interest Aluminium (Al), Silica (Si), Titanium (Ti) and Zirconium (Zr), as fluctuations in CPS. The cluster analysis (right hand side of figure) identifies distinct sediment layers using coloured lines to demark, sort into similar groups then cluster together into larger groups with defined boundaries. The groups clearly identify the major stratigraphic units in the profile where the first is from 0-450 mm (zone 1) and the second is from 510-910 mm (zone 2). For cores 2 the zones are 0-350 mm and 350-760 mm, and core 3 are 0-370 mm and 370-760 mm (Appendix 6). This statistical and more robust evidence focuses on detrital elements as identified by the ITRAX scans and PCA (Appendix 2; Fig 5.13) and supersedes the preliminary core analyses that identified three distinct stratigraphic boundaries based on the entire sediment characteristics (Fig 5.11).

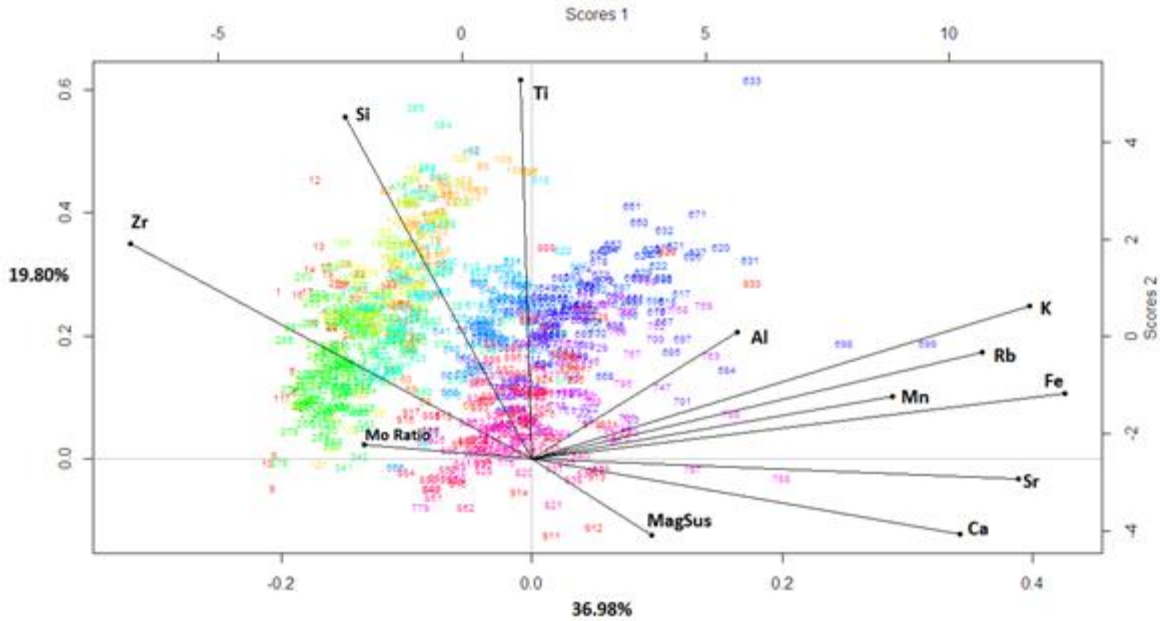

Figure 5.13: *The correlation bi plot shows the principal components for Old Boo core 1. The detrital and pedogenic elements appear to correspond to the zones identified in (Fig 5.14). This is shown by the colours green, yellow, orange and light blue colours plotting together in the top half of the core; and the colours pink, red, and purple plotting together from the bottom half of the core. This suggests that the detrital elements are more dominant in the top 50cm as opposed to pedogenic elements at depth.*

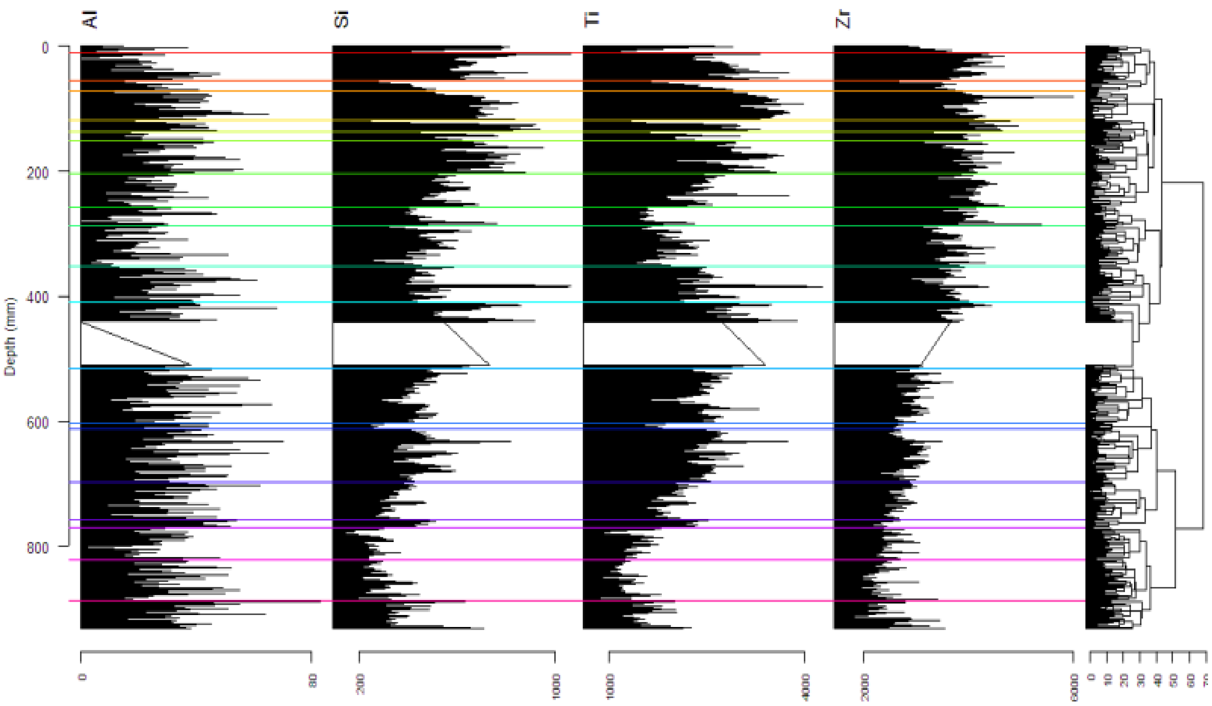

Figure 5.14: *Stratigraphic plots of ITRAX results for core 1 from Old Boo wetland showing the detrital (Si Ti Zr) and pedogenic (Al), elements of interest; and the fluctuations in CPS. Cluster analysis suggesting two stratigraphic units on the far right. The gap from 45-50 cm is a join in the cores which coincides with the boundaries and is represented by the cutting shoe.*

This is consistent with the enrichment toward the surface for Si, Ti and Zr, however, it may be partly an artefact of elemental concentration due to pedogenesis at depth, and is a relative increase in those elements. Therefore, in addition it is necessary to examine elemental ratios. Two humps are clear when observing the Si and Ti data which indicate a change in geochemistry especially at a depth of 300 mm, whilst Zr shows a pronounced enrichment toward the surface. Although Al is normally associated with clay, it displays steady CPS and significant peaks occur at intervals of around 200 mm. Despite negligible enrichment, the bottom section of the core appears to have higher clay content reflected in the CPS but the PSD suggests minimal clay throughout. The aluminium may be present as pedogenic aluminium (hydroxides), which would account for its clustering with other pedogenically mobile elements. Pair wise correlations for the elemental suite were performed to show the strength of the linear relationships between each element in the profile (Appendix 7).

5.5.3 Elemental ratios as proxy indicators

The elemental ratios focused solely on elements Al, Si, Ti and Zr (Fig 5.15). These lithogenic elements were selected because they are geochemically stable and hosted by minerals resistant to weathering. Further, they are useful proxies for catchment erosion, change of grain size and changing mineralogy (Boes et al*.,* 2011). Ti/Zr displays a variable distribution with increases at 10 and 50 cm, followed by a decrease in the ratio at 0, 30 and 76 cm. These variations are interspersed with a spike approximately every 15 cm. Si/Zr has a distinct surface enrichment from 30 cm with many closely aligned peaks. A decline in the ratio occurs at 10 cm, 30-50 cm then the values increase from 50-76 cm. Si/Ti exhibits a pattern with a steady ratio from 0-30 cm. A prominent spike is seen at 35 cm which is followed by a decline until 70 cm where the ratio increases until 76 cm. Si/Al also shows the surface enrichment trend starting from 30 cm the ratio increases markedly with several spikes and the biggest occurring at 10 cm. From 30 cm a down-core decline is observed, however, there is a slight increase from 65-76 cm. The Si/Al and Si/Ti show higher values in the top 30 cm, which could mean that higher quartz to clay ratio indicative of coarser particles from an increase in sandy or from finer silty detrital inputs from the catchment, creeks or forest tracks.

5.5.4 Calibration of ITRAX results

The ITRAX data (CPS) were converted to concentrations (mg kg^{-1}) to allow quantitative comparison of elemental concentration values (Fig 5.16A-H). The elemental suite of interest comprised pedogenically mobile Potassium (K), Calcium (Ca), Manganese (Mn), Iron (Fe), and Rubidium (Rb) and detrital (Ti and Zr) elements, as identified by the PCA analyses above, whose range had more variation in the profile (Appendix 2). Linear regression between the ITRAX and pXRF revealed that relationships between elements were from very strong (R^2 = 85.45 for Zr); to weak (R^2 = 26.79 for Mn) (Appendix 8). The patterns in the calibration results suggest that elements with a greater atomic weight are more accurate.

The ITRAX proxy indicator for organic content (Molybdenum Incoherent / Molybdenum coherent) displayed no correlation to LOI data. At the time of scanning, the sediment was quite dry and brittle with several deep horizontal cracks toward the surface shown in the radiograph (Fig 5.11). The cracks and moisture may have partly affected the accuracy of CPS in these sections.

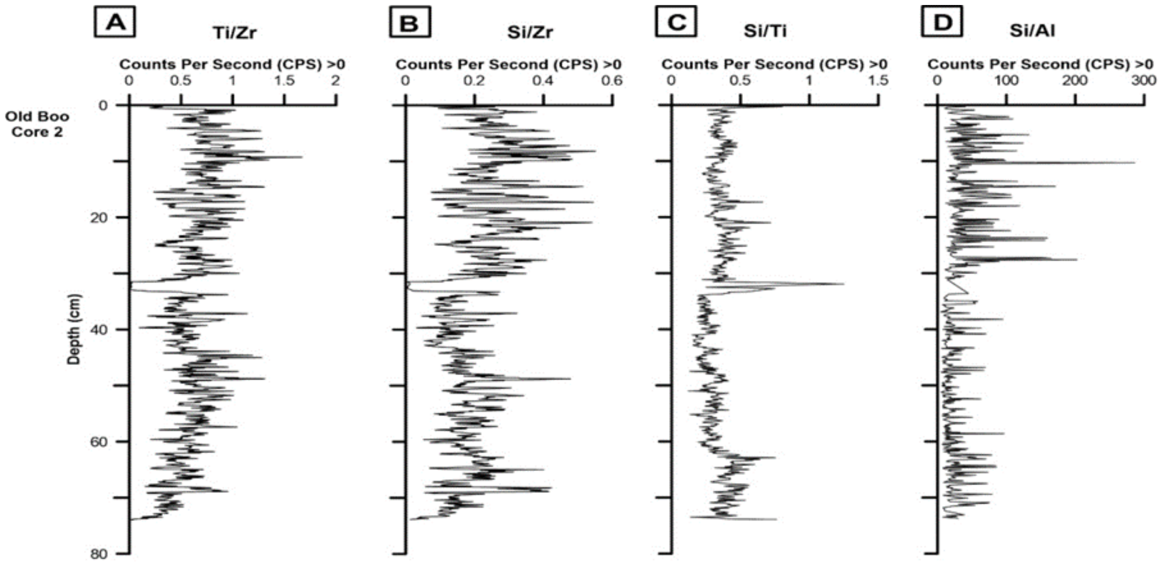

Figure 5.15: *Elemental ratios **(A)** Ti/Zr; (**B**) Si/Zr; **(C)** Si/Ti and **(D)** Si/Al for Old Boo core 2.*

The 1 mm ITRAX scan interval illustrated the finer details and captured micro changes in the geochemistry not recorded by the pXRF samples at 2 cm intervals (Fig 5.16). Both sets of results have a similar pattern, however, clearly displaying the enrichment of detrital elements (Zr and Ti) at the core top; and pedogenically mobile elements (K, Ca, Mn, Fe, Rb and Strontium (Sr)) at the bottom of the core (Fig 5.16). Although there are clearly some discrepancies in peak concentrations, the overall changes throughout the profile are detected with some accuracy in both sets of results (Fig 5.16).

5.6 Sediment Geochronology

5.6.1 pOSL

Portable OSL data from the three wetlands all show significant fluctuations in total photon counts for IRSL and BLSL, which may indicate a change in depositional environment and/or stratigraphic boundaries. Generally, the luminescence intensity for each wetland sediment profile (A) Old Boo core 2 (B) PW3 core 3 and (C) PW1 core 1, show a clear trend (Fig 5.17). That is, the IRSL and BLSL total photon counts increase with depth. The photon counts for the top 20 cm of each profile increase steadily with depth. Between 20 and 50 cm the total photon counts have a stepped increase. However, PW3C3 displays a reduction in photon counts from 12-20 cm which may indicate deposition of incompletely bleached sediment, low dose rate sediment, or sediment mixing. The peak luminescence counts for both IRSL and BLSL occur at a depth deeper than 55 cm. The peak is followed by a pattern of slight decrease and increase in photon counts until the luminescence becomes stable for the remainder of the profile. Assuming that age is the dominant driver of pOSL signal in these sediments, it appears that there are two units: a much older unit below around 55 cm depth and a younger unit above 55 cm which continues to accumulate steadily today.

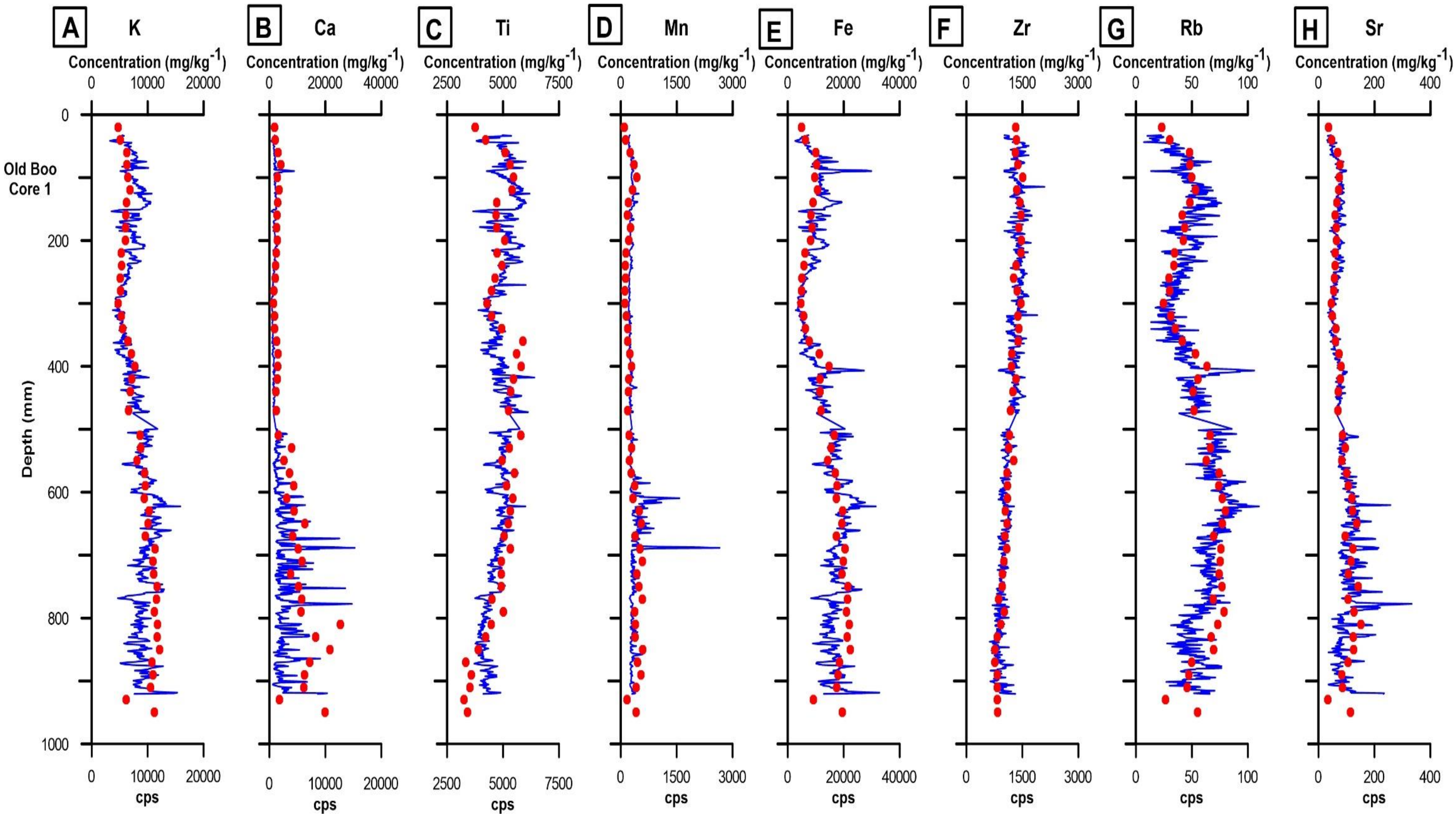

Figure 5.16: *Old Boo core 1 elemental concentration profiles were developed by calibrating the pXRF and ITRAX instruments for (A) K; (B) Ca; (C) Ti; (D) Mn; (E) Fe; (F) Zr; (G) Rb, and (H) Sr. The blue line is the ITRAX data in CPS at 1 mm intervals and the red dots are pXRF mg/kg at 2 cm intervals.*

5.6.2 Establishing numerical age (^{14}C)

The pre-treated samples for Old Boo cores 1-3 all had very low Carbon (%) content (Appendix 9). The highest was 0.13% (PW2-C3 20-25 cm), and 0.02% the lowest is observed in 2 samples (PW2-C2 40-45 cm; PW2-C3 45-50 cm). This may have affected the reliability of the deeper radiocarbon ages in cores 2 and 3, although there is no independent test available, these results must be interpreted with caution. The unexpectedly old ages observed in PW2-C3 45-50 cm (18 359 cal BP) and PW2-C2 40-45 cm (13 773 cal BP) correspond to the samples with the lowest Carbon content. The other ages are PW2-C1 20-25 cm (2370 cal BP) and 40-45 cm (6725 cal BP); PW2-C2 20-25 cm (8331 cal BP), and PW2-C3 20-25 cm (2089 cal BP). Age-depth plots for the cores illustrate the difference in age and sedimentation rates between the cores (Fig 5.18). It appears that C2 is older for the same depth than C1, indicating a different recent history. C3 may have a hiatus between 22.5 and 47.5 cm. The ages of C2 and C3 at 40-45 cm and 45-50 cm, respectively, are difficult to reconcile with the pOSL behaviour (Fig 5.17) which shows a break to likely much older values below around 55 cm. There is no hint in the pOSL data of a large difference in age between the radiocarbon sample depths.

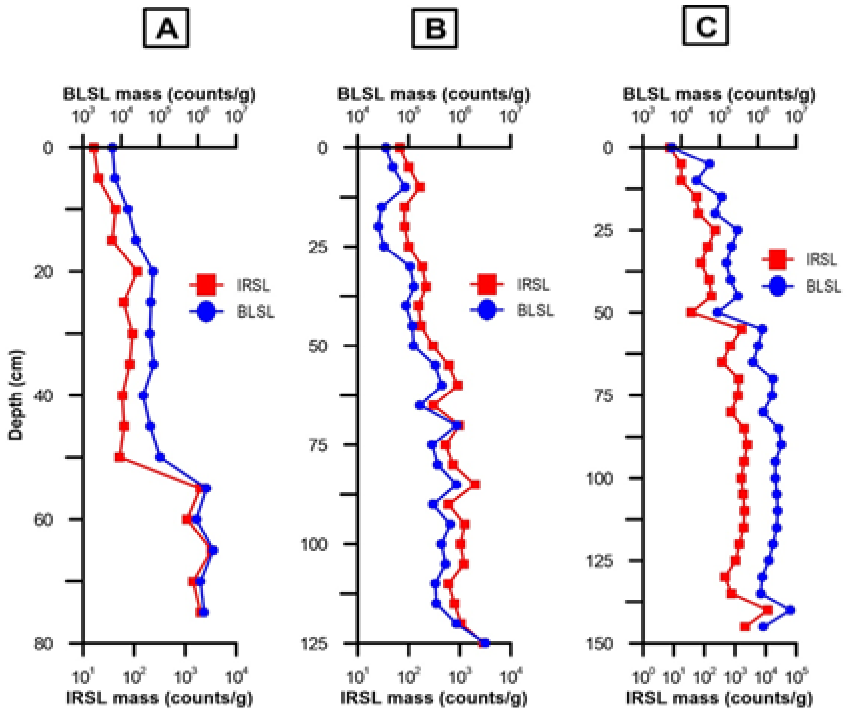

Figure 5.17: *pOSL data from the three wetlands showing the IRSL and BLSL intensities for (A), Old Boo core 2 (B) PW3 core 3 and (C) PW1 core 1 normalised by total photon counts/weight (grams).*

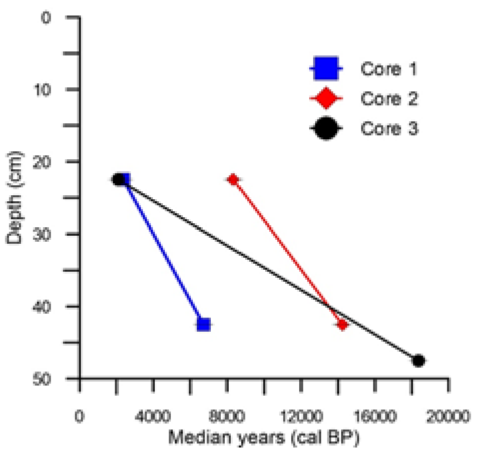

Figure 5.18: *Age-depth plots for the radiocarbon ages calibrated before present (cal BP) from the three Old Boo sediment cores; core 1 (C1), core 2 (C2) and core 3 (C3). Error bars are very small but they show the sigma 1 range.*

5.6.3 Excess ^{210}PB

Total, supported and unsupported (excess) ^{210}Pb concentrations were determined for the top 20 cm of the sediment profile at Old Boo core 1 (Fig 5.19A-D). The excess ($^{210}Pb_{ex}$) activities exhibited a monotonic decline from 0-12 cm in the profile and the excess activities from 12-20 cm were very low, which is an indication that excess activity was at background levels. From this data mass accumulation rates (g/cm^2/year) and sediment ages were calculated using the CRS model and a two-zone CIC model.

Age-depth models were also constructed (Fig 5.19E-F). The profile was split into two zones (0-5 cm and 5-12 cm) and a change in accumulation rate between the zones was identified as 0.075 cm/year and 0.214 cm/year, respectively. Using the CRS model, mean sedimentation rates were 0.15 and 0.08 cm/year. Sediment ages from both models were in close agreement, within the uncertainty ranges, with the age at 10-12 cm given as 89±15 years (CIC) and 98 ±10 years (CRS).

The excess ^{210}Pb inventory at Old Boo was found to be ~206 mBq/cm^2, ^{210}Pb flux ~64 Bq/m^2/year and initial excess activity at surface was 65 Bq/kg. These results are comparable to the mean excess ^{210}Pb inventory from the Macquarie Marshes reference sites 150 km west of the Pilliga Forest (Ralph, 2008; Ralph et al., 2011). In addition, excess ^{210}Pb reached background levels at similar depths at the reference sites, which were assumed to be 'static', therefore without erosion or deposition, which implies a dominance of atmospheric excess ^{210}Pb supply. To validate the ^{210}Pb chronology, radiocarbon (n=6) was used to calculate ages and derive sedimentation rates before present (BP).

A comparison between the ^{210}Pb chronology and radiocarbon for core 1, revealed vastly different model predictions for ages and sedimentation rates. The CRS model predicts an age of 68 and 95 years with sedimentation rates of 0.075 and 0.214 cm/year between 0 and 5, and 5 and 11 cm, respectively. At the same depth the radiocarbon model predicts that the age is 1160 cal. years BP, assuming a steady sedimentation rate of 0.1 cm / year between 22.5 cm and zero years at the surface.

At face value, this indicates that the sediment rate has increased tenfold between 22.5 cm and 11 cm. However, it is possible that ^{210}Pb has leached or been mixed down through the profile and does not represent the true age; or that low Carbon content has resulted in inaccurate radiocarbon ages. While these possibilities cannot be excluded, the results are tentatively accepted here as they stand since there is no direct contradiction between them.

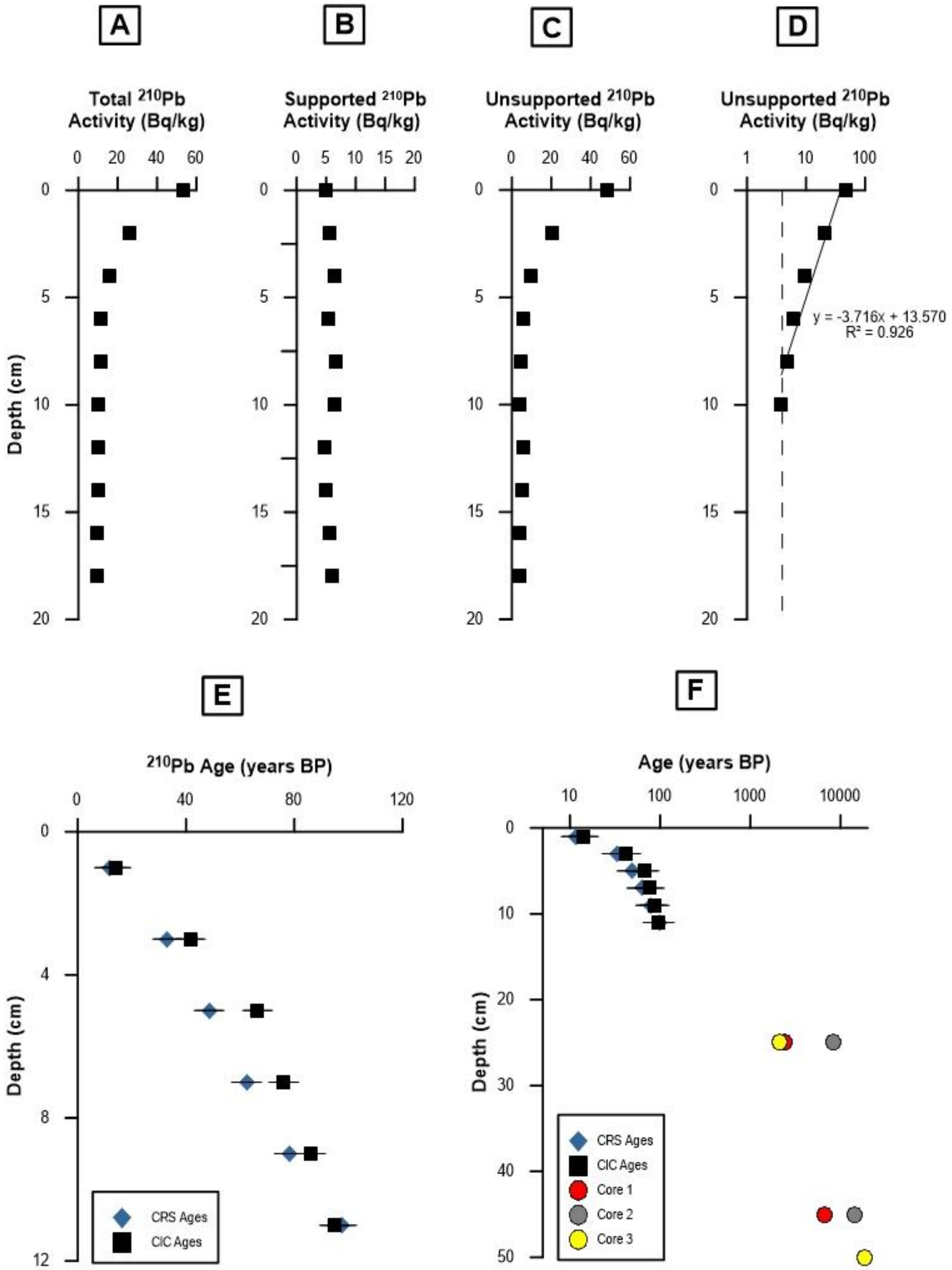

Figure 5.19: *This figure shows the **(A)** Supported ^{210}Pb activity; **(B)** total ^{210}Pb activity; **(C)** unsupported ^{210}Pb activity; **(D**) unsupported ^{210}Pb activity linear regression out puts showing the line of best fit for the age-depth estimation; **(E)** age estimates from the modified CIC model (black square) and the CRS (blue diamond), and **(F)** ^{210}Pb compared with radiocarbon on a log scale (red, yellow and grey circles).*

5.7 Wetland Ecology

The presence and absence analysis uncovered biological remains of aquatic plants and animals in Old Boo core 1 (Yoshi Kobayashi pers comms. 2015; Appendix 10). A total of six groups were found. Of these, two were plants, diatoms and charophytes (as oospores), and four were animals including freshwater sponges (as spicules), chironomids (as head capsules), bivalves and cladocerans (as head shields) (Appendix 11). The freshwater sponges were found at depths ranging from 0-93 cm and were the most frequently found (n=40), followed by charophytes (n=17) and diatoms (n=8) whose distribution was limited to the top 34 cm of the profile. Apart from the sponges, the three other animal remains distribution was limited to the top 4 cm in depth, presumably because of dissolution and decay at depth.

The groups discovered fill different niches in the wetlands. They have different tolerance thresholds to chemico-physical conditions such as wet and dry phases, and sensitivity to stressors like eutrophication (Tibby et al., 2003; Yu et al., 2015). The Sponges prefer slow moving shallow waters (Manconi and Pronzato, 2008) and are shown to have persisted in this environment for some time (Gooderham and Tysrlin, 2002). Conversely, the charophytes are a benthic macroscopic algae preferring deeper water and require sufficient water to propagate (Garcia, 1994, Schneider et al., 2015). Their shallower distribution suggests it is a more recent coloniser. The frequent occurrences of charophytes, coupled with those of diatoms, indicate a significant environmental change in the wetland for a time period corresponding to the sediment core from a depth of ~30 cm to the surface. These results suggest that this may mark more substantial, wet periods in the last few thousand years.

6.0 Discussion

6.1 Validating environmental history

The age model was determined by the combined ^{210}Pb (n=10 from core 1 only) and ^{14}C (n=6 over 3 cores) results and by constructing age depth plots and extrapolating sedimentation rates (Fig 6.1). The limitations and uncertainties of these ages and the age model were raised in chapter 5. In brief, these relate to the low carbon yield of the radiocarbon samples, the small number of ages, the apparently different histories of the three cores, and the potential that the ^{210}Pb profile is modified by diffusion downward, rather than upward sediment accumulation. Therefore ages (cal BP) and sedimentation rates (cm / yr) from the age models must be seen as tentative. The anomaly in the sedimentation rate from the ^{210}Pb inventory could possibly be the product of low bulk density values closer to the surface or be caused by compression in the top 20 cm. However, the bulk density data indicated that minimal compression had occurred because the values were confined within a small range as confirmed by the statistical analysis (Mean 1.02; ST Dev 0.09) (Appendix 9).

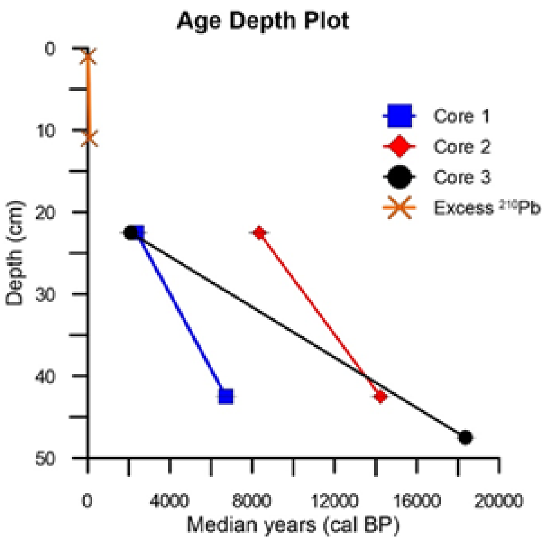

***Figure 6.1**: Age depth model showing the ^{210}Pb and ^{14}C ages for the cores from Old Boo. The angle of the lines gives an indication as to the sedimentation rates, and how this changed within the site. Note the marked increase in sedimentation rate for core 1 indicated by the ^{210}Pb analyses.*

The following sections discuss the environmental history of the wetlands, based on the proxy evidence presented in chapter 5 and the chronology derived from the age model. Two main sediment facies, and time periods are indicated: an older fluvial deposit (zone 1) and the younger wetland deposit (zones 2-4). Discussion primarily focuses on the more complete record of core 1, and evidence drawn from cores 2 and 3 are used to support the inferences made.

Zone 1: >15 cal yr BP late Pleistocene increased fluvial activity and wetter periods

The basal fluvial facies, which was indicated by coarse sand (Fig 5.11, 5.12) and the lack of aquatic organisms (Fig 6.2), begins below the deepest sediment recovered, 40 ka in core 3, and continues to ca. 15 ka in all three cores (Fig 6.2). Core 1 shows an increase in mud content ca. 15 ka. There is a decline in mud content before and ca. 18 ka, with it being as low as 25% in core 1, and much lower in cores 2 and 3. This reflects a late Pleistocene environment with humid conditions, higher fluvial activity which increased unit stream power and an ability to transport higher calibre sediments fed by runoff (Fitzsimmons et al., 2013) (Fig 6.2A).

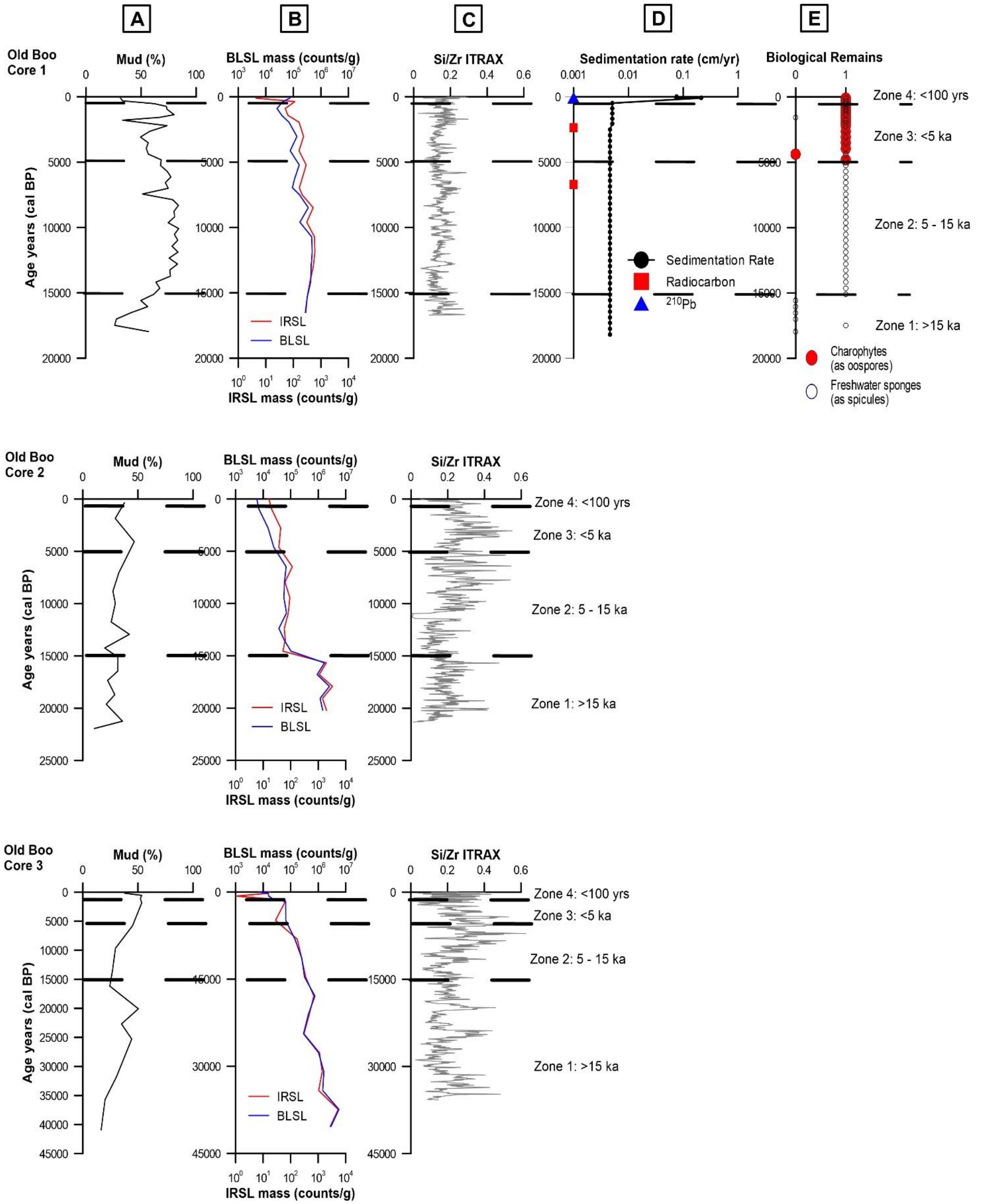

Figure 6.2: *Selected data **(A)** Mud % from the particle size distribution, **(B)** pOSL profile, **(C**) Si/Zr ITRAX, for Old Boo cores 1-3, and **(D)** Sedimentation rates from the age depth model, **(E)** Biological remains of two taxa (charophytes and freshwater sponges) in core 1**.***

The absence of freshwater sponges in this zone (Fig 6.2E) supports the absence of standing water and suggests a well-connected channel-floodplain system, thus forming an efficient drainage system. Interestingly in core 3 the mud content is lowest ca. 40 ka, and this coincides with the formation of sand monkeys, palaeochannels which filled with sand as they stopped conveying water, elsewhere in the Pilliga Forest (Hesse and Humphreys, 2001). This drainage system weakened and the channels avulsed some time during this period as the sediment input from the catchment dissipated (Young et al., 2002).

The pOSL (Fig 6.2B) shows a clear trend where the age of the sediment continues to increase steadily with depth, more pronounced in core 2, where total photon counts peak at the boundary to zone 2. The lower Si/Zr (Fig 6.2C) and high sand content may be a reflection of higher energy streams transporting the sediment more efficiently. The sediment was therefore transported toward the Namoi, unlike the present day where sediment is stored in channel and valley margins (Young et al., 2002). The southward avulsion of the Namoi supports a shift in the hydrological regime with less water in the catchments ca. 15 ka. The wetlands become less connected to the creeks as the fluvial system became less efficient in transporting flow (Young et al., 2002).

***Zone* 2: Late Pleistocene to Mid Holocene 5 – 15 ka cal yr BP**

The wetland facies began at ca. 15 ka and its first phase ended at ca. 5 ka (Fig 6.2). The PSD suggests that the sediment calibre became finer and more silt was present in the profile, as reflected by the mud content in core 1 at 15 ka, and 12 ka in core 2 (Fig 6.2A). Generally, the increase in the mud content delineates the shift as conditions changed from fluvial to wetlands. The fine sediment represents a low energy back swamp environment as the mud settles out on the distal floodplain, and forms an impermeable layer of sediment that is capable of holding water for prolonged periods. After the onset of wetland conditions the records indicate a period of relative stability from ca. 15 ka until ca. 8 ka indicative of a wetter period with consistent rainfall. The Si/Zr in cores 2 and 3 show a distinct increase from ca. 8–5 ka followed by a decline in mud content, suggesting the start of a transition to drier conditions at ca. 6 ka was preceded by a wetter period.

The wetlands have previously been described as 'tank gilgai' (Bell et al., 2012). Gilgai processes involve the swelling and cracking of heavy clay in an alternating wetting and drying environment (Yonge and Hesse, 2009). However, from the topography observed during this study it is unlikely that gilgai formed the wetlands, but may play a subsidiary role. The formation of the subsoil fragipan is more likely the major cause of formation and maintenance of the wetlands. Fragipans are a complex and poorly understood pedogenic horizon involving a degree of interstitial cementation by silica and iron. When the water levels fall and the wetland becomes dry the fragipan hardens forming a hydrological boundary on top of the sandy material. Observations made in this study show that gilgai cover a small proportion of the wetland surfaces. In some cases the deep gilgai were dry while the adjacent shallow basins held water and aquatic plants, consistent with penetration of the fragipan by gilgai cracking. In this sense, the gilgai may be destructive of the water-holding capacity of the wetlands.

The wetlands may have formed on the edge of the floodplain or in drainage lines that had become less efficient in transporting flows and this caused deposition of sandy material in close proximity to the channels. This created basins on the distal floodplain where less available water within the catchment meant more water was captured and stored within the basins during seasonal flows. These basins trapped the fine silt and clay transported in suspension. Similar circumstances formed and maintained the few small basin-type (lentic) wetlands at the Macquarie Marshes (150 km west) (Yonge and Hesse, 2009).

The trends of the period, spanning from the late Pleistocene through the early-mid Holocene, are described in emerging literature expanding the resolution of palaeoclimate in South East Australia (Gouramanis, et al., 2013; Petherick et al., 2013; Reeves et al., 2013). Generally, they identify a climate that was initially cooler and drier following the LGM, then a stable warmer and wetter climate (deglaciation period), that transitioned to variable conditions which coincided with the strengthening of ENSO at ca. 6-4 ka. The palaeoecological data implies that the freshwater sponges, which prefer standing or slow flowing water, were dominant during the Late Pleistocene to Mid Holocene interval. However, this apparent dominance could also be an artefact of preservation processes and the destruction of other taxa in the oxidising conditions of the wetland sediments.

Zone 3: Late Holocene variable climate <5 ka cal. yr BP

This interval is characterised by higher sand content (at least in core 1) and charophytes. Deeper water environments, such as the inset basin at present day Old Boo, store runoff and remain as wildlife refuges after storm events. More frequent filling of this basin after ca. 5 ka may have provided the conditions more suited for growth of charophytes. This is consistent with the disconnection of the wetlands from the surrounding creeks as the ability to transport water through the system dissipated due to the lower availability of surface water. The onset and then strengthening of the ENSO, ca. 6-4 ka, coincides with this time frame (Fitzsimmons et al., 2013). The climate became cyclic, more variable and longer drier periods occurred but also alternating with intense wet periods (La Niña). This has caused a shift to a more ephemeral hydrological regime and increased aridity in the landscape in the Pilliga and in palaeoclimate records elsewhere in Australia (Shulmeister, 1999).

The cyclic hydrologic regime (wet and dry phases) is suggestive of a variable climate and hydrological regime with fluctuations of sand and mud content (Fig 6.2A). The higher sand content (>50%) may indicate flood events such as that experienced in 2011 which transported sand sheets from the surrounding catchments into the outwash province and wetlands (Michael Murphy pers comms. 2015). The pOSL (Fig 6.2B) illustrates the younger sediment inputs, perhaps from the storm and flood pulses specific to summer-dominated rainfall. An increase in silica (quartz) (Fig 6.2C) toward the surface was found in core 1. This may be partly explained by the formation of a beach immediately to the southwest of the core site, on the northwestern shore of the lake, in response to the dominant summer southeast wind direction and the shallowing of the lake at the core 1 site.

The deeper and more permanent water is reflected by the presence of charophytes which are benthic organisms that prefer to be fully submerged and inhabit low energy environments (Schneider et al., 2015). The presence of charophytes occurred around the same time as the switch from the more ephemeral wetland (zone 2) to an ephemeral lake. However, the absence of oospores below 34 cm may be an artefact of poor preservation in the alternately wet and dry muds of the basin. The presence of other taxa (diatoms) from 26 cm indicates that an aquatic ecosystem has formed over the last several thousand years.

The presence of an Indigenous population was well established during this time (Humphreys, 2007; OEH, 2012) and the use of fire as a management tool may have played a part in increasing sedimentation. However, due to poor preservation of charcoal in the profile, it is unclear what impacts may have occurred.

Zone 4: European occupation and management <100 years

The most recent zone is characterised by a period of European land management and intensified land use in the catchments. This has seen a considerable decline in mud content and a shift to a wetter phase (Fig 6.2A). There appears to be a new younger sediment being deposited rapidly as shown by a significant decline in pOSL photon counts (6.2B) and a sudden increase in sedimentation rates over the last 100 years (Fig 6.2D). An increase in the Si/Zr ratio at the transition between zones 3-4 may indicate the landscape response to an altered management regime (Fig 6.2C).

The sedimentation rate increased rapidly in the last century, which was then followed by a decrease, as shown by the ^{210}Pb inventory (Fig 6.2D). However, caution must be used when making such interpretations because the change in sedimentation rate also occurs when changing from radiocarbon to ^{210}Pb chronologies. A possible source for the new, younger sandy sediment may be forest operations in the catchment of Old Boo. The long history and mechanised extraction, fire suppression and high frequency stochastic rainfall events may generate sediment and transport it down stream, where it is deposited (vertically accreting) in the wetlands. The increased input of sandy material declines ca. 50 years ago and the most logical explanation for this decline is the creation of the Gilgai Nature Reserve in 1968 which later became the Pilliga National Park. A halt to logging operations within the protected area surrounding the wetlands is reflected in the landscape's response that exhibits an apparent recovery and lower sedimentation rates.

A diverse aquatic ecosystem has developed over the last few decades, where six taxa are found in the top 4 cm of sediment. Increasing diversity may also be an indication of a wetter period, and that wet and dry phases are still capable of maintaining the aquatic communities. Additionally, commercial forestry could be assisting in maintaining the wetlands as fire and low surface roughness by conveying the runoff more readily overland and ultimately is captured in the depressions. The construction of forestry roads could provide an additional source of sediment and act as a conduit for run-off into the wetlands.

6.2 Accelerated trajectory*:* catchment and wetlands

The purpose of this research was to determine the trajectory of environmental change in the Pilliga Forest, and whether or not the changes have caused geomorphic instability that affects the creeks, floodplain and wetlands; and if so, whether the changes were the result of European management regimes (commercial forestry activities) and have been catastrophic, as suggested by Rolls (1981). There has been limited research within the Pilliga to ascertain or quantify such change so this study provides new information to deduce temporal and spatial scales of such change and identifies how they have and will affect the catchment and wetlands.

The Pilliga has a relatively long human history with the Gamilaraay believed to have inhabited the area since the Mid Holocene and to have used fire as the main management tool (Oxley, 1820; OEH, 2012). In comparison, the European period has been relatively short, punctuated by intensified land use, resource exploitation and ongoing climate change. The findings of this study suggest that this has caused the trajectory of change to accelerate. In essence, the European legacy is placing the wetlands on the floodplain in danger.

Vegetation structure and Geomorphic response

A change in vegetation structure is believed to be a leading cause of geomorphic instability and there has been debate surrounding exactly how and whether this occurred due to European Management (Ryan et al., 1995, Benson and Redpath, 1997; Butzer and Helgren, 2005). One popular viewpoint is that early settlers who sought to create productive agriculture enterprises drastically altered the vegetation structure and its composition (Rolls, 1981). A contrasting viewpoint is that the vegetation simply reverted to its original successional state with the removal of fire stick farming (Gammage, 2011). An objective of this study was to test whether the change in vegetation and altered fire regimes has led to a cascade of geomorphic instability; to deduce temporal and spatial shifts in sediment deposition or erosion and to assess the current status of the catchment's creeks, floodplains and wetlands.

The level of geomorphic adjustment was difficult to ascertain. There had been some recent change reflected in a small knickpoint and scouring of the beds at Goona and Coghill Creeks (Fig 5.10E-F). Despite these observations, which are related to an increased unit stream power; no firm conclusion could be reached as to whether catastrophic change in the creeks had occurred. Continued logging operations and their impact were likely to be the cause of hillslope and floodplain erosion seen to be transporting sediment down slope to the channel of Coghill Creek. The channels of Mollieroi, Goona and Coghill Creek were covered in a loose sandy deposit, consistent with a sediment slug and the ideas of Rolls (1981) of sanding up (aggradation) of sediment in the creeks (Fig 5.9, Fig 5.10A-B). Nonetheless, no early-European surveys were located to compare against these observations and so it is not possible to definitively say if the sandy beds are part of the natural condition of channels in this landscape or the product of alteration.

Sedimentation and Hydrological response

The investigation revealed a complex micro topography with fluvial and wetland facies at Old Boo. Although no detailed analyses were undertaken on PW3 and PW1, they also shared similar stratigraphy and sediment characteristics with Old Boo, that is, a higher calibre of sediment at depth and fining up toward the surface (Fig 5.11). A band of yellow medium sand was observed in the top 30 cm of PW1. This was likely from recent disturbance, driving of vehicles that exacerbated surface erosion and run off from forestry tracks. There was sand spread across the surface of the other wetlands away from the margins and tracks, most likely from rain splash sorting leaving behind a sandy layer.

The geochronology revealed that the major change seen at Old Boo was the dramatically higher sedimentation rate of the last ≈100 years. The changes were also noted in the pOSL results across the three wetlands and were consistent with a hastening deposition due to forestry operations, management techniques and the changing of fire regimes (Rolls, 1981). The contemporary management may have created a situation where high intensity fire is influential and become a geomorphic agent, which could have influenced the sedimentation budget and yield (Shakesby and Doerr, 2006).

The effects of bushfire on the floodplain in the upper catchment were clear, as a denuded landscape with large areas of exposed soil was observed. The removal of fire-tolerant *Eucalyptus* species by ringbarking and logging has meant that areas of the fire-sensitive *Callitris* take longer to re-establish when completely burnt which could leave the surface susceptible to erosion (Rolls, 1981; Thompson and Eldridge, 2005). The effect of high intensity fire may have provided the conditions where erosion was not only more likely, but created a hydrophobic soil surface that readily transported liberated sediment across the flood plain and into the creeks after a storm event (Shakesby and Doerr, 2006). The observations in this study revealed that a winter storm and average monthly precipitation in June 2015 had suspended, entrained and transported sediment down the hillslopes into the creeks. Despite only minimal amounts of sediment reaching the creeks these observations were enlightening as to the landscape response in the event of a high magnitude storm event. The amount of rain needed to surpass flow thresholds and move sediment into the creeks was >50 mm (Section 5.3.1). The majority of the area's rainfall occurs in summer, with January recording the highest average monthly total at 83.3 mm (Fig 3.2A). Therefore, average rainfall >80 mm provide the conditions that could transport large volumes of sediment and this is most likely to occur in the summer months.

A higher magnitude summer storm event or flood after an intense fire or drought associated with ENSO phases would likely entrain more sediment from a bare surface and could also activate the flashy flow regime. (Cawson et al., 2012). This could move the large amounts of sediment to and deposit in the wider channel downstream and could conceivably transfer sediment across the floodplain and infill the wetlands (Nynan et al., 2011). However, the factors assumed above are reliant on the hydrological capacity and the connectivity of the creeks to the wetlands. Given that they are disconnected, sediment delivery from creek to wetland could be inhibited (Fryirs, 2013). A LiDAR topographic survey and intensive fieldwork following a flood event is required to test this hypothesis.

The sediment budget could also be influenced by the extensive unsealed forestry road network throughout the Pilliga and the Coghill Creek catchment. The roads intersect the creeks in the head waters with no controls on sediment inputs, and run close to the boundary of the wetlands (Fig 5.5). Evidence of inputs to the creeks was seen during this study with rill erosion transporting sediment along pre-existing pathways developed during past storm events (Fig 5.10C-D). Additionally, the thin bands of yellow medium sand found in the top 30 cm of cores from PW1 was of a very similar calibre and composition to the forestry roads/tracks immediately adjacent to the wetland (Fig 6.3A). The roads are covered in loose sand, had minimal embankments and were significantly disturbed by the use of recreational motor bikes and four wheel drives (Fig 6.3B).

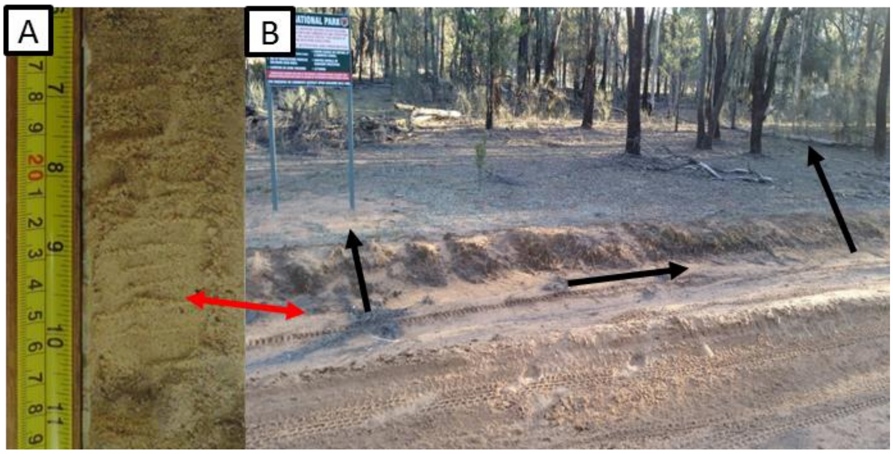

***Figure 6.3: (A)** The marginal core (PW1C3) closest to the forestry roads/tracks showing the sandy bands in the top 30 cm, and **(B)** The forestry roads/tracks which run alongside the wetlands with very similar sand. The black arrows show the possible routes of sand to reach the wetlands. Old Boo and PW1 were much closer to the forest tracks and had less topographic barriers for sediment flow paths.*

The roads come within metres of the shores of Old Boo and PW1, and shed runoff and sediment into the wetlands. It is likely that the forest roads are the biggest immediate threat to the wetlands because of the cumulative impacts and ongoing sediment input despite their small surface area in the Pilliga (Croke et al., 1999; Fu et al., 2009). The small distance that sediment had to travel was sloping towards the wetland, with limited surface roughness at the boundary and would likely channel the suspended sediment into the depressions and gilgai. Forestry roads/tracks can potentially provide more sediment than the forested areas around the wetlands and the broader local catchment combined (Motha et al., 2004).

Ecological response and climate controls

The forestry industry has operated in the Pilliga Forest for the last 100 years or more. Initially the industry was small but it expanded until going into decline in the 1980’s (Whipp, 2009). The quota system of harvesting was applied as a means to effectively manage the resources but extensive extraction of vegetation from semiarid lands is thought to increase water availability (Tunstall et al., 1981). The increased water yield in deforested catchments can lead to the formation and maintenance of wetlands (Woodward et al., 2014b). The shift to a positive water balance is associated with increased water availability as the hydrologic regime shifts and water declines in the rivers or creeks but increases in floodplain wetlands. The phenomenon is thought to have created many RAMSAR listed wetlands and the management of these is reliant on the processes that maintained them. Alteration of the water balance by incorporating management activities to restore vegetation may lead to the decline of the wetlands (Woodward et al., 2014b).

This study revealed that a complex aquatic ecosystem has developed, especially during the last 100 years (Fig 6.2E). This ecological change is reflected by water depth and longevity of inundation where semi-permanent water holes such as Old Boo are able to sustain aquatic communities for longer periods. The preservation of biological remains is influenced by taphonomy and the semiarid environment does not provide ideal conditions for preservation. Therefore, caution must be used when using one core and coarse presence and absence data to characterize palaeoecological change (Ralph et al., 2011). The accretion of sediment on floodplain wetlands as a result from European management is of concern in the Pilliga, the MDB and elsewhere as sediment fluxes in higher order streams threaten their longevity (Gell et al., 2009).

This study also found that change has occurred over the last 15 ka driven by changes in boundary conditions, that is, climate change associated with glacial, deglacial and ENSO regimes, that has shaped the hydrological regime and ecology in the region. These changes occurred steadily over time as the landscape adjusted to new conditions. A decrease in fluvial activity and a shift in vegetation type occurred within similar intervals which highlights climate controlled-feedbacks (Dodson, 1989; Young et al., 2002). It has been argued that the dominant process was an intensification of atmospheric circulation (Woodward et al., 2014b). This controlled moisture availability, precipitation and runoff in a wetter period from ca. 8-5 ka, before falling precipitation and increased variability occurred due to ENSO (Fig 6.2A). The evidence from the last 100 years at Old Boo shows that sedimentation may be a response to European management in the catchment (Fig 6.2D), but the change observed is not catastrophic as previously claimed (Rolls, 1981). The primary influence could be climate change and this thesis presents a low resolution record missing key support proxies such as charcoal and stable isotopes, which can give only limited guidance for the management of the wetlands.

6.3 Contemporary management

The development and maintenance of a wetland-specific environmental management plan followed on from the recommendations of the study conducted by Bell et al (2012) and was implemented by the statement of management intent (OEH, 2014). This is comprised of passive and active management strategies, community awareness and private conservation plans for wetlands outside the boundary of protected areas, coordinated by the National Parks and Wildlife Services. The primary threats have been identified as feral pigs, weed invasion, anthropogenic disturbance, climate change, forestry and sedimentation. Provisions have been made to ensure the ecological values and the integrity of the wetlands remains with feral animal control, limitation of recreational vehicle access, signposting, monitoring weeds and sediment. A fire management strategy is also in place to protect biodiversity that contains back burning provisions.

The data gathered during this study has shown high sedimentation accommodation within the channels of the surrounding catchment. The risks to the wetland are that a flood pulse may activate the drainage, liberate sediment and deposit it overbank during floods. The progression downstream of a sand blanket (or 'slug') may increase the risk of a stochastic infill event within the wetlands. Surface roughness must be maintained along the floodplain to act as a buffer for in-coming sediment. The monitoring of sediment flux from service roads could also be measured by using sediment traps along the boundary of the wetlands. If they are indeed a large sediment source then consideration should be given to their relocation. The gilgai processes on the surface of the wetlands may be more problematic. Little is known as to the formation and processes of gilgai, however, the formation and cracking of the impermeable sub-soil may allow water to drain away into the water table. Therefore the wetlands' longevity, ecological communities, and functions are threatened by geomorphic processes that reduce their water holding capacity.

The climate predictions for South East Australia (SEA) are of a continued inter annual variability (ENSO) with an increase in mean annual temperatures which have risen 0.9 ^{O}C during the last century with each decade being warmer since 1950 (Head et al., 2014). This increase and low rainfall has recently caused prolonged drought (Millennium Drought '1999-2006'), severe heat waves (Angry Summer 2012-13), saw record maximum temperatures and enhanced conflagrations with catastrophic bushfire events (Black Saturday) associated with El Niño. Conversely, the strengthening La Niña driven by sea surface and atmospheric temperatures saw extreme precipitation over SEA in 2010-11. These conditions were the wettest since instrumental records began and caused extensive flooding which also affected the Pilliga (Head et al., 2014). This inter-annual variation and the extreme weather events have implications for the long term management of the wetlands ecology and the refugia it provides. Recent wetter conditions (June 2015) and evidence of recent fires (January 2015) could have forestry tracks and catchment inputs equally threaten the longevity of the wetlands. The Southern Oscillation Index (SOI) forecasts the 'Godzilla El Niño' for 2015 with strongly negative (-15) values which exemplifies the variable boom and bust cycle (BOM, 2015b). The relationship between climate drivers and altered fire regimes is clear. The increase in fire activity, due to a warming climate, will affect global fire regimes which carries serious implications for management (Daniau et al., 2012).

6.4 Study limitations and directions for future research

This study applied a broad multi-proxy and presented new data for the Pilliga Forest and the endangered wetlands**.** Despite this, there remains an opportunity to further investigate environmental change in the Pilliga by addressing the limitations encountered during this study. The low carbon content in the sediment and the small number of radiocarbon ages could have provided an erroneous age range for the wetlands. At present the age-depth model accuracy in determining sedimentation rates is questionable. Further, a low inventory of ^{210}Pb, from only one core, means that there are no records to support the findings of higher recent sedimentation rates. These factors complicate interpretation of the geochronology and cause uncertainties in making predictions from the evidence. The incorporation of Optical Stimulated Luminescence (OSL) to date the cores may assist to constrain the ages and substantiate the geochronology.

The topographical data relied on one arc second (30 m) DEM and the accuracy were significantly affected by too much surface noise (trees). The use of LiDAR to map the Coghill Creek and other catchments, their hydrological connections and local catchment boundaries surrounding the wetlands would be beneficial in obtaining the most accurate data capable of revealing the hydrological connections of the wetlands to their catchments.

The palaeoecological data could be improved by using stable isotopes (^{13}C; ^{15}N) and/or their ratio (C:N) to detect minor fluctuations in the environment. Such analyses are planned but could not be completed by the deadline for this thesis. These would complement the presence and absence observations for biological remains, which have limited utility due to the semi-arid conditions not being conducive for preservation, and convey more clearly the ecological changes and or shifts in trophic levels in the wetlands. Expanding the sampling scale and selecting multiple wetlands would also assist in developing a suite of information to characterise the wetland types. Also sampling the creek beds and banks in the catchment to examine sedimentology, geochemistry, minerology (XRD) and OSL may inform as to geomorphic adjustments and constrain the time frame in which this aggradation (sanding up) had occurred.

The extraction of macro or micro charcoal from the sediments would assist in quantifying fire regimes and act as an index of fire for the wetlands' and the catchment. Specifically, it could determine if the fire regimes were in fact altered and what impact they had by detecting fluctuations in fire frequency and temporal shifts from natural to, Gamilaraay and European regimes. The erosion processes could also be investigated to model sediment inputs into creeks from hillslopes and from forest roads into the wetlands using plot scale methodology. Additional proxies may assist in developing a complete Holocene record for the Pilliga Forest. An in depth conceptual model of the biophysical processes could be developed to inform management of landscape configuration and positive feedbacks.

7.0 Conclusions

The main hypothesis of this research was that the European management regime had altered the geomorphic, hydrological and ecological processes in the Coghill Creek Catchment, and that this is threatening the endangered wetlands on the floodplain because of increased erosion and sedimentation rates. It was hypothesised that the wetlands were of Holocene age, formed by water perched above the impermeable fragipan at the margins of the floodplains as hydrologic efficiency of the fluvial system dissipated. The processes that maintained them were driven by ENSO (wet and dry phases), and that gilgai modified them but were not responsible for their formation.

This hypothesis has tentatively been corroborated, as increased sedimentation rates from the ^{210}Pb inventory coincides with the European management in the catchment. The elevated sedimentation rates will ultimately be detrimental to the floodplain wetlands if they continue along the same trajectory. Forestry practices have most likely altered the hydrologic regime by reducing surface roughness, causing erosion and contributing to the sediment budget. However, the hypothesis could also be contradicted because the same sequence of events may also have inadvertently created more runoff into the depressions and gilgais, enhancing the wetlands. This provided more frequent fills that sustained ecological communities and the aquatic ecosystem diversified over the last hundred years with more taxa being present than in previous intervals.

The wetlands were much older than expected, being established prior to the Holocene. Although it is confirmed from the PSD data that ENSO influence occurred from ca. 6 ka, the evolution from river to wetlands, which became ephemeral lakes, had actually started in the late Pleistocene. The wetlands are not maintained solely by ENSO driven processes but also by the generally poor catchment connectivity in the drier post-glacial regime.

7.1 Major findings

The major findings of this thesis are directly related to the aims of the research:

1) *Determine the age of the wetlands in the Coghill Creek catchment; and to identify what is or was their characteristic hydrology, and the principle geomorphic processes that formed and maintained them;*

> The radiocarbon ages revealed that the wetlands were older than expected. They were of Holocene age at depths of 40–45 cm, but were conceivably much older at the onset of wetland conditions and during the fluvial phase. It is difficult to confirm the exact ages for the wetlands due to sparse age estimates. The sedimentology revealed the characteristic depositional environment and how this shifted in response to climate and European management. It appears that the hydrologic efficiency decreased in tandem with declines in precipitation leading to fine sediment being deposited on the floodplain adjacent to the channel. Suspended fine sediment in the top 50 cm formed an impermeable barrier which allowed water to accumulate which was indicated by the presence of aquatic macrofossils.

***2)** Assess downstream geomorphological change of streams leading to the wetlands at the catchment scale to determine flow thresholds, geomorphic adjustments and disturbance*;

It was difficult to assess the downstream geomorphic change and adjustments due to the lack of early-European surveys to compare against these observations and so it is not possible to definitively say if the sandy beds are part of the natural condition of channels in this landscape or the product of alteration. Flow thresholds were able to be deduced from observations in the catchment and the effect of average rainfall in entraining and transporting sediment in the landscape.

***3)** Identify sediment sources, storage and transport zones in the Coghill Creek catchment to deduce spatial and temporal shifts in sediment deposition and erosion;*

The main sources of the sediment were derived from the Pilliga sandstone province and the increase in the last 100 years is most likely a result of forestry operations and altered fire regimes. An increased sediment yield was generated from exposed surfaces on the hillslopes which were liberated during post fire storm events. The transport zones in the middle of the catchment were identified by wide channels filled by a sand slug. The forestry tracks were also identified as, perhaps, the primary source to the wetlands because of ongoing inputs as the creeks were disconnected from and flooding was rare. Although it was conceivable that one stochastic event could have a significant impact on the wetlands, it was more likely that the main danger to the wetlands' longevity come from the forestry tracks.

***4)** Evaluate the current status of the wetlands, creeks, and floodplains*;

The current status of the three wetlands surveyed varied due to level of disturbance. PW1 had considerable damage to the surface from motor vehicles and from feral pig foraging. Old Boo contained water during both field trips so it was possible to ascertain that it was semi-permanent. There was evidence of erosion and sediment input from the local catchment on the southern boundary. PW3 appeared relatively intact as it was separated from the forestry tracks by a vegetated floodplain which may buffer impacts. The creeks showed signs of recent disturbance and were aggrading. The floodplains were heavily vegetated and/or bare from recent fires.

***5)** Develop an understanding of the biophysical processes in the Coghill Creek Catchment and how they are likely to influence the future trajectory of the wetlands.*

The main biophysical processes that were likely to influence the trajectory of the wetlands were erosion, sedimentation and runoff. Currently the wetlands are largely isolated from the broader catchment processes because they are disconnected from the stream network and protected from sediment input by both somewhat incised channels and a broad very well vegetated floodplain. Changes to any of these conditions could threaten the health of the wetlands.

8.0 References

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9.0 Appendices

9.1 Appendix 1 – Sampling and Sub-Sampling Procedures

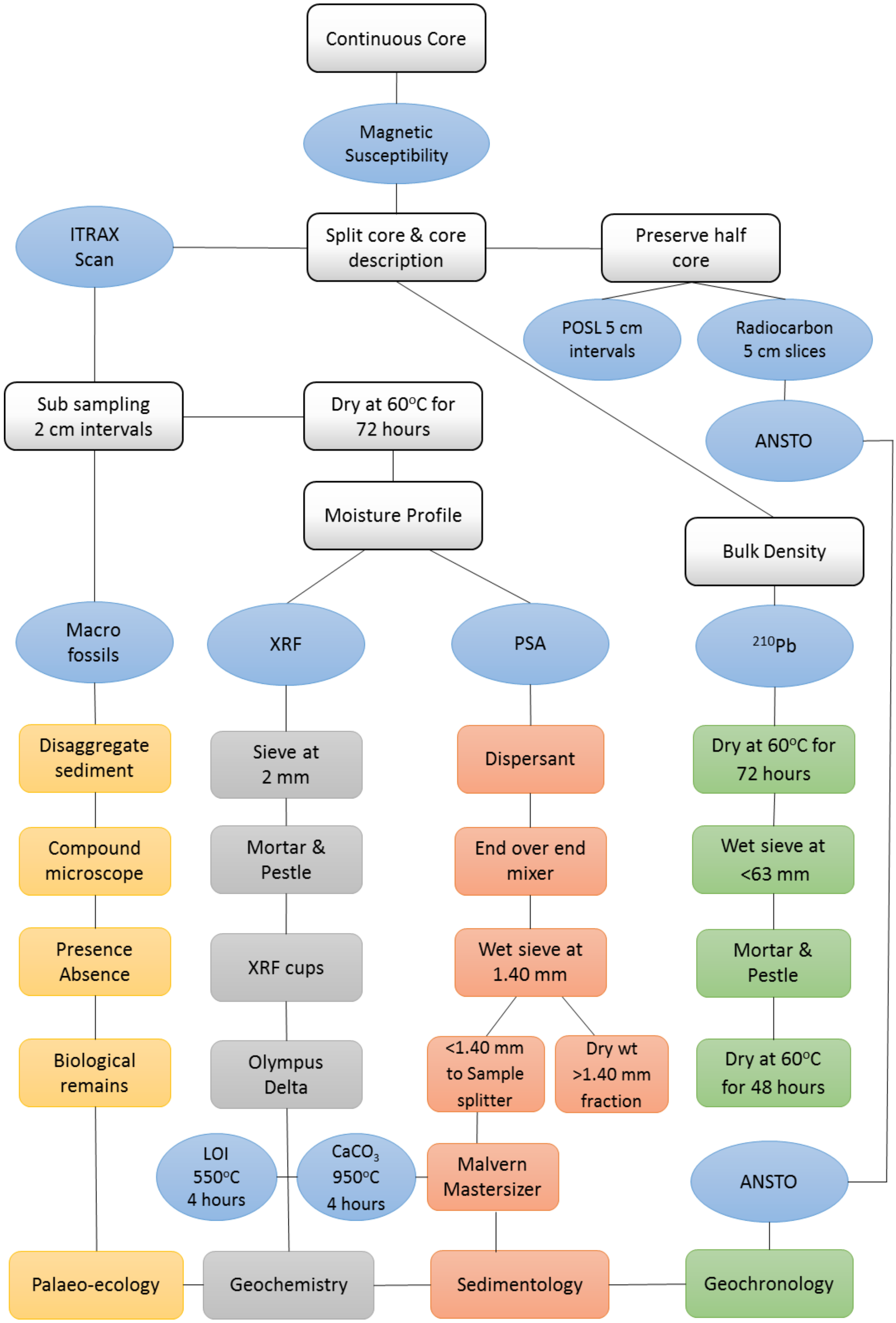

Figure 9.1: *Flowchart of sampling and sub sampling procedures conducted during this study.*

9.2 Appendix 2 – ITRAX Profiles

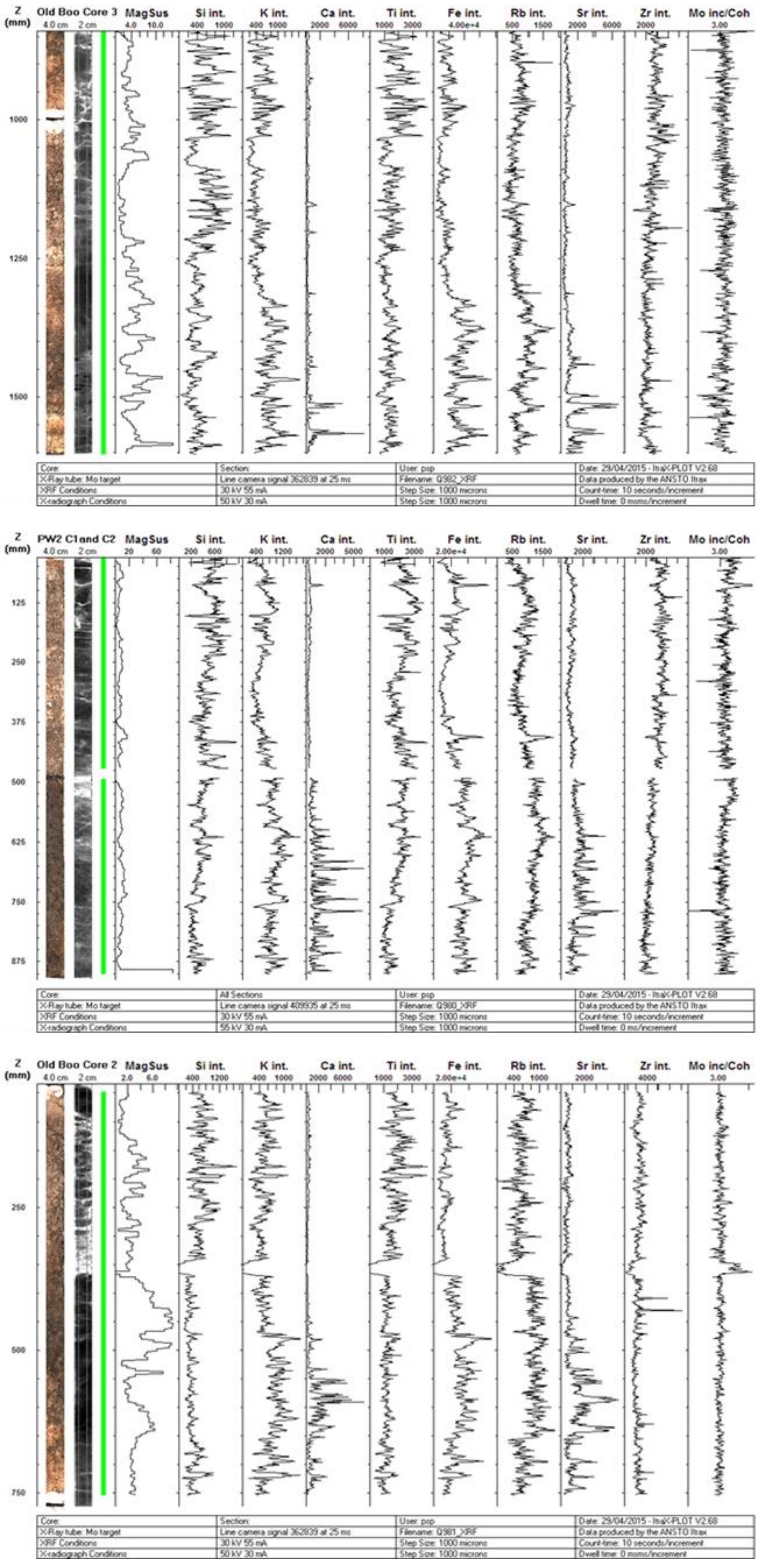

Figure 9.2: *ITRAX element profiles for cores 1, 2 and 3 at Old Boo wetland.*

9.3 Appendix 3 - QAQC

Table 9.1: *ITRAX and pXRF Elements*

Element	ITRAX	pXRF	Element	ITRAX	pXRF
Silver (Ag)		x	Niobium (Nb)		x
Aluminium (Al)	x		Neodymium (Nd)		x
Argon (Ar)	x		Nickel (Ni)	x	x
Arsenic (As)		x	Phosphorus (P)	x	x
Barium (Ba)	x	x	Lead (Pb)	x	x
Bismuth (Bi)		x	Praseodymium (Pr)	x	x
Bromine (Br)	x		Rubidium (Rb)	x	x
Calcium (Ca)	x	x	Sulfur (S)	x	x
Cadmium (Cd)		x	Antimony (Sb)		x
Cerium (Ce)	x	x	Selenium (Se)		x
Chlorine (Cl)	x	x	Silicon (Si)	x	
Cobalt (Co)		x	Tin (Sn)		x
Chromium (Cr)	x	x	Strontium (Sr)	x	x
Caesium (Cs)	x		Tantalum (Ta)		x
Copper (Cu)	x	x	Thorium (Th)		x
Iron (Fe)	x	x	Titanium (Ti)	x	x
Hafnium (Hf)	x		Uranium (U)		x
Mercury (Hg)		x	Vanadium (V)		x
Potassium (K)	x	x	Tungsten (W)		x
Lanthanum (La)	x	x	Yttrium (Y)	x	x
Manganese (Mn)	x	x	Zinc (Zn)	x	x
Molybdenum (Mo)		x	Zirconium (Zr)	x	x

Table 9.2: *The precision (RPD) and accuracy (RSD) data recorded for each CRM. The mean RPD and RSD for all CRM's are also shown.*

CRM	%	K	Ca	Ti	Mn	Fe	Rb	Sr	Zr
NIST 2709a	RPD	18.18	7.01	3.13	0.06	9.93	4.71	17.71	158.97
	RSD	2.10	0.66	0.54	0.55	0.49	0.96	2.62	0.34
NIST 2710a	RPD	4.47	2.15	6.57	3.13	12.57	2.28	21.31	321.50
	RSD	1.19	0.68	2.79	1.93	0.39	1.21	1.14	0.63
NIST 2711a	RPD	10.68	0.47	12.39	11.46	13.53	1.72	17.63	NC
	RSD	0.32	0.58	0.68	0.54	0.67	1.24	1.73	1.27
CNRC BCSS-1	RPD	NC	NC	15.49	1.89	9.63	NC	24.65	NC
	RSD	NC	NC	0.82	2.61	0.43	0.60	0.48	0.27
CNRC PACS-2	RPD	14.76	5.44	8.18	7.58	7.18	NC	25.24	NC
	RSD	1.76	0.22	0.99	1.60	0.22	0.64	0.84	1.87
Total Mean RPD		10.51	3.44	8.72	4.54	10.90	2.75	21.31	267.32
Total Mean RSD		1.34	0.54	1.16	1.45	0.44	0.93	1.36	0.88

Table 9.3: *Comparison of actual value of standard material NIST2709a and measured value from pXRF. SD = standard deviation, SE = standard error, RPD = relative percent difference, RSD = relative standard deviation.*

	K (mg kg^{-1})	**Ca** (mg kg^{-1})	**Ti** (mg kg^{-1})	**Mn** (mg kg^{-1})	**Fe** (mg kg^{-1})	**Rb** (mg kg^{-1})	**Sr** (mg kg^{-1})	**Zr** (mg kg^{-1})
Actual value NIST2709a	21100	19100	3360±70	529±18	33600 ±700	99	239±6	195
Measured Mean	17263	20439.67	3255	528.67	30265	94.33	281.33	505
Measured SD	363.33	135.88	17.69	2.89	148.86	0.91	7.37	1.73
Measured SE	209.77	78.45	10.21	1.67	85.94	0.52	4.26	1.00
RPD%	18.18	7.01	3.13	0.06	9.93	4.71	17.71	158.97
RSD%	2.10	0.66	0.54	0.55	0.49	0.96	2.62	0.34

Table 9.4*: Comparison of actual value of certified reference material NIST2710a and measured value from pXRF.*

	K (mg kg^{-1})	Ca (mg kg^{-1})	Ti (mg kg^{-1})	Mn (mg kg^{-1})	Fe (mg kg^{-1})	Rb (mg kg^{-1})	Sr (mg kg^{-1})	Zr (mg kg^{-1})
Actual value NIST2710a	21700	9640	3110±70	2140±60	43200 ±800	117	255±7	200
Measured Mean	22669.33	9432.67	3314.33	2207	48631.33	119.67	309.33	843
Measured SD	269.06	64.52	92.34	42.67	188.82	1.44	3.51	5.29
Measured SE	155.34	37.25	53.31	24.64	109.02	0.83	2.03	3.06
RPD%	4.47	2.15	6.57	3.13	12.57	2.28	21.31	321.50
RSD%	1.19	0.68	2.79	1.93	0.39	1.21	1.14	0.63

Table 9.5*: Comparison of actual value of certified reference material NIST2711a and measured value from pXRF.*

	K (mg kg^{-1})	Ca (mg kg^{-1})	Ti (mg kg^{-1})	Mn (mg kg^{-1})	Fe (mg kg^{-1})	Rb (mg kg^{-1})	Sr (mg kg^{-1})	Zr (mg kg^{-1})
Actual value NIST2711a	25300	24200	3170±80	675±18	28200 ±400	120	242±10	NC
Measured Mean	22597.67	24087.00	2777.33	597.67	24385.67	122.07	284.67	1093.67
Measured SD	73.42	140.30	18.77	3.21	164.17	1.52	4.93	13.87
Measured SE	42.39	81.00	10.84	1.86	94.78	0.88	2.85	8.01
RPD%	10.68	0.47	12.39	11.46	13.53	1.72	17.63	NC
RSD%	0.32	0.58	0.68	0.54	0.67	1.24	1.73	1.27

Table 9.6*: Comparison of actual value of certified reference material CNRC BCSS-1 and measured value from pXRF.*

	K (mg kg^{-1})	Ca (mg kg^{-1})	Ti (mg kg^{-1})	Mn (mg kg^{-1})	Fe (mg kg^{-1})	Rb (mg kg^{-1})	Sr (mg kg^{-1})	Zr (mg kg^{-1})
Actual value CNRC BCSS-1	NC	NC	4400±143	229±15	32873 ±979	NC	96	NC
Measured Mean	16369.33	5157.33	3718.33	224.67	29706.67	92.53	119.67	762.67
Measured SD	73.66	142.52	30.35	5.86	129.02	0.55	0.58	2.08
Measured SE	42.53	82.28	17.52	3.38	74.49	0.32	0.33	1.20
RPD%	NC	NC	15.49	1.89	9.63	NC	24.65	NC
RSD%	NC	NC	0.82	2.61	0.43	0.60	0.48	0.27

Table 9.7*: Comparison of actual value of certified reference material CNRC PACS-2 and measured value from pXRF.*

	K (mg kg^{-1})	Ca (mg kg^{-1})	Ti (mg kg^{-1})	Mn (mg kg^{-1})	Fe (mg kg^{-1})	Rb (mg kg^{-1})	Sr (mg kg^{-1})	Zr (mg kg^{-1})
Actual value CNRC PACS-2	12400	19600	4430±320	440±19	40900 ±600	No CRM	276±30	NC
Measured Mean	10570.33	18533.67	4067.67	406.67	37963.00	68.20	345.67	466.00
Measured SD	186.23	41.43	40.28	6.51	82.61	0.44	2.89	8.72
Measured SE	107.52	23.92	23.25	3.76	47.70	0.25	1.67	5.03
RPD%	14.76	5.44	8.18	7.58	7.18	NC	25.24	NC
RSD%	1.76	0.22	0.99	1.60	0.22	0.64	0.84	1.87

9.4 Appendix 4 – Coring Results

***Table 9.8**: Summary of the coring results (n=9).*

Wetland	Core #	GPS location	Actual Penetration (cm)	Sediment Recovery (cm)	+ Cutting Shoe (cm)	Total Core Length (cm)	Ratio of Recovery
Old Boo	1	30.50308ºS 149.34148ºE	91.5	91	4	95	0.97
	2	30.50335ºS 149.34180ºE	95	76	4	80	1.19
	3	30.50305ºS 149.34259ºE	82	77	3	80	1.03
PW3	1	30.50716ºS 149.36195ºE	150	149.5	0	149.5	1.00
	2	30.50715ºS 149.36210ºE	148	139.5	0	139.5	1.06
	3	30.50755ºS 149.36272ºE	130	127	0	127	1.02
PW1	1	30.50666ºS 149.37107ºE	150	146	4	150	1.00
	2	30.50705ºS 149.37133ºE	132.5	127.5	4	131.5	1.01
	3	30.50691ºS 149.37139ºE	153	145	4	149	1.03

9.5 Appendix 5 – Principle component analyses

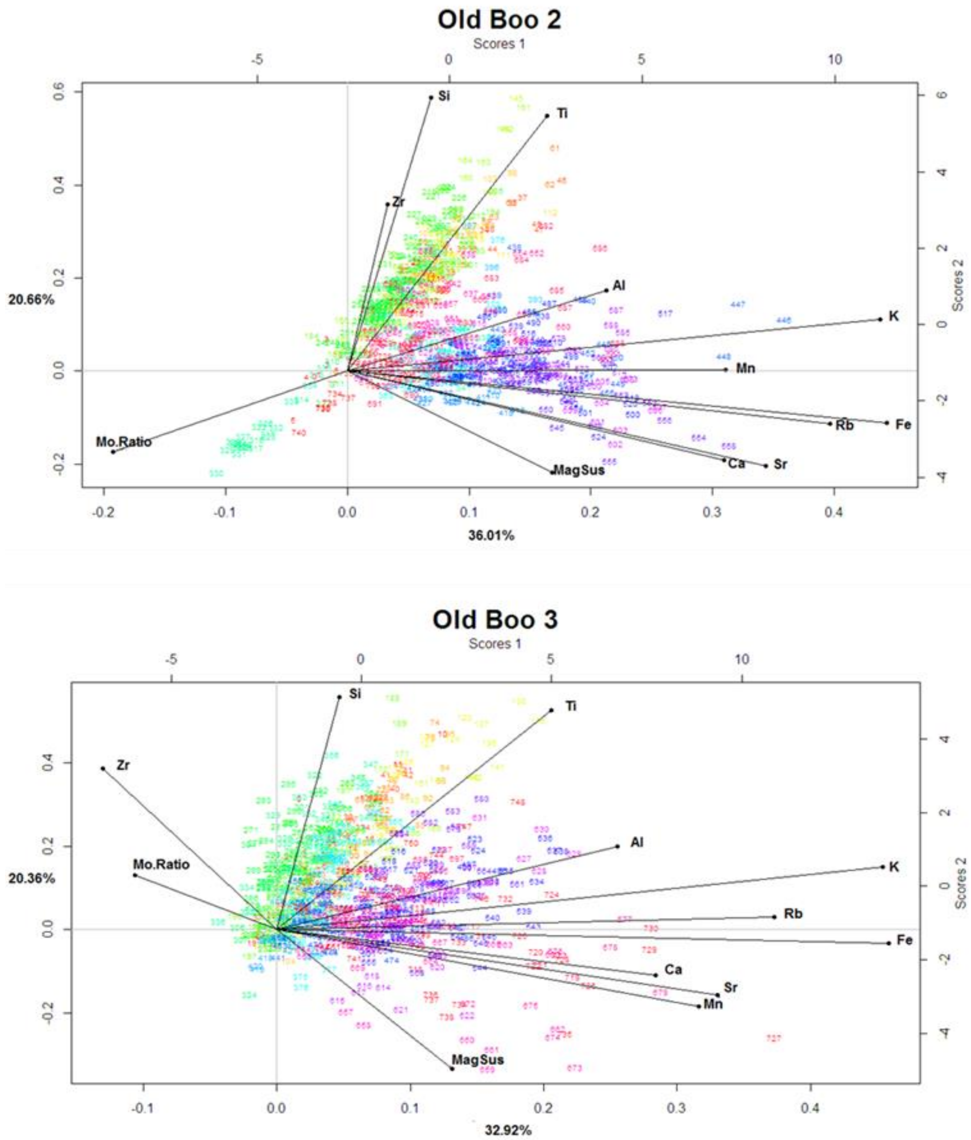

***Figure 9.3:** Correlation bi plots for Old Boo cores 2 and 3*

9.6 Appendix 6 – ITRAX detrital element cluster analysis plots

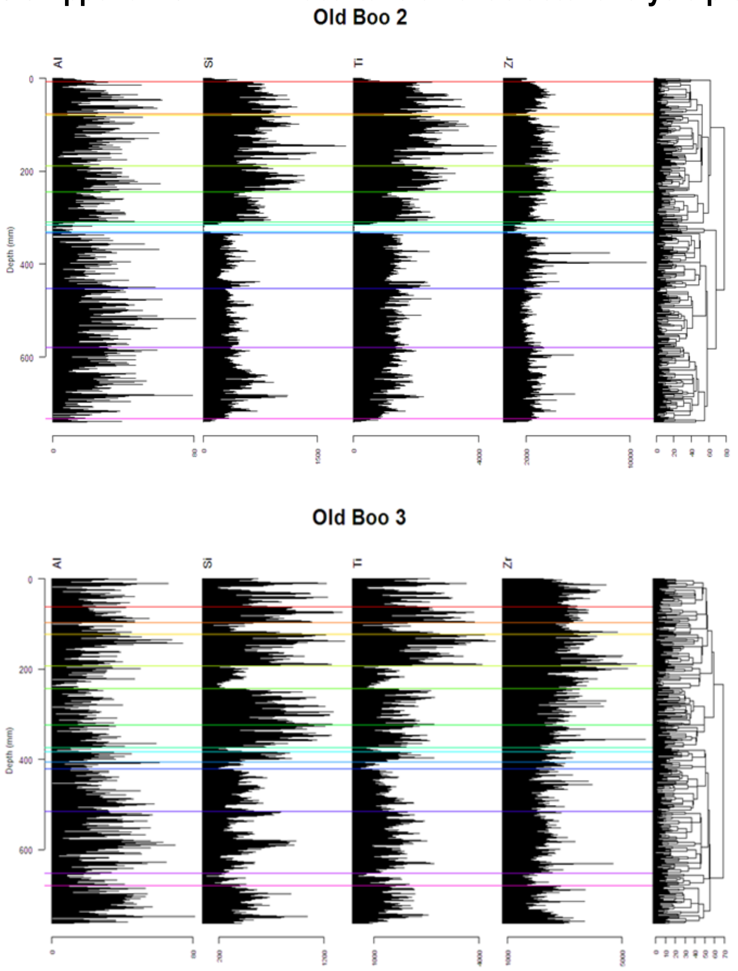

Figure 9.4: *Stratigraphic plots with cluster analyses for Old Boo cores 2 and 3.*

9.7 Appendix 7 – Correlation matrix of ITRAX elemental data

Table 9.9: *Pair wise correlation show the strength of linear relationships between elements for Old Boo core 1.*

Core 1	Al	Si	K	Ca	Ti	Mn	Fe	Rb	Sr	Zr	Mag Sus	Mo. Ratio
Al	1.00	0.11	0.35	0.16	0.18	0.15	0.31	0.27	0.18	-0.12	0.01	-0.07
Si	0.11	1.00	0.07	-0.25	0.80	-0.05	-0.19	-0.14	-0.26	0.63	-0.16	0.04
K	0.35	0.07	1.00	0.44	0.34	0.46	0.91	0.72	0.56	-0.44	0.10	-0.19
Ca	0.16	-0.25	0.44	1.00	-0.17	0.48	0.46	0.28	0.77	-0.47	0.14	-0.25
Ti	0.18	0.80	0.34	-0.17	1.00	0.13	0.13	0.24	-0.03	0.51	-0.08	0.06
Mn	0.15	-0.05	0.46	0.48	0.13	1.00	0.47	0.37	0.44	-0.24	0.07	-0.18
Fe	0.31	-0.19	0.91	0.46	0.13	0.47	1.00	0.78	0.61	-0.59	0.13	-0.08
Rb	0.27	-0.14	0.72	0.28	0.24	0.37	0.78	1.00	0.57	-0.35	0.07	-0.11
Sr	0.18	-0.26	0.56	0.77	-0.03	0.44	0.61	0.57	1.00	-0.44	0.10	-0.31
Zr	-0.12	0.63	-0.44	-0.47	0.51	-0.24	-0.59	-0.35	-0.44	1.00	-0.21	0.08
Mag Sus	0.01	-0.16	0.10	0.14	-0.08	0.07	0.13	0.07	0.10	-0.21	1.00	-0.07
Mo. Ratio	-0.07	0.04	-0.19	-0.25	0.06	-0.18	-0.08	-0.11	-0.31	0.08	-0.07	1.00

Table 9.10: *Pair wise correlation show the strength of linear relationships between elements for Old Boo core 2.*

Core 2	Al	Si	K	Ca	Ti	Mn	Fe	Rb	Sr	Zr	Mag Sus	Mo. Ratio
Al	1.00	0.26	0.42	0.16	0.29	0.19	0.34	0.27	0.17	0.04	0.02	-0.14
Si	0.26	1.00	0.33	-0.10	0.87	0.08	-0.05	-0.10	-0.14	0.38	-0.32	-0.21
K	0.42	0.33	1.00	0.49	0.45	0.55	0.90	0.69	0.54	0.06	0.17	-0.30
Ca	0.16	-0.10	0.49	1.00	-0.03	0.30	0.50	0.39	0.80	-0.13	0.07	-0.19
Ti	0.29	0.87	0.45	-0.03	1.00	0.25	0.15	0.14	-0.02	0.41	-0.12	-0.27
Mn	0.19	0.08	0.55	0.30	0.25	1.00	0.61	0.46	0.29	-0.03	0.20	-0.13
Fe	0.34	-0.05	0.90	0.50	0.15	0.61	1.00	0.82	0.60	-0.08	0.38	-0.23
Rb	0.27	-0.10	0.69	0.39	0.14	0.46	0.82	1.00	0.53	0.07	0.48	-0.26
Sr	0.17	-0.14	0.54	0.80	-0.02	0.29	0.60	0.53	1.00	-0.08	0.15	-0.25
Zr	0.04	0.38	0.06	-0.13	0.41	-0.03	-0.08	0.07	-0.08	1.00	0.08	-0.26
Mag Sus	0.02	-0.32	0.17	0.07	-0.12	0.20	0.38	0.48	0.15	0.08	1.00	-0.12
Mo. Ratio	-0.14	-0.21	-0.30	-0.19	-0.27	-0.13	-0.23	-0.26	-0.25	-0.26	-0.12	1.00

Table 9.11: *Pair wise correlation show the strength of linear relationships between elements for Old Boo core 3.*

Core 3	Al	Si	K	Ca	Ti	Mn	Fe	Rb	Sr	Zr	Mag. Sus	Mo. Ratio
Al	1.00	0.24	0.49	0.15	0.34	0.16	0.41	0.30	0.13	-0.04	0.01	-0.06
Si	0.24	1.00	0.26	0.01	0.76	-0.09	-0.03	-0.04	-0.12	0.35	-0.42	0.07
K	0.49	0.26	1.00	0.32	0.54	0.42	0.92	0.70	0.39	-0.17	0.16	-0.07
Ca	0.15	0.01	0.32	1.00	0.10	0.44	0.31	0.20	0.71	-0.16	0.05	-0.15
Ti	0.34	0.76	0.54	0.10	1.00	0.08	0.30	0.29	0.06	0.42	-0.18	0.02
Mn	0.16	-0.09	0.42	0.44	0.08	1.00	0.49	0.23	0.47	-0.25	0.29	-0.23
Fe	0.41	-0.03	0.92	0.31	0.30	0.49	1.00	0.76	0.45	-0.32	0.30	-0.12
Rb	0.30	-0.04	0.70	0.20	0.29	0.23	0.76	1.00	0.41	-0.10	0.17	-0.03
Sr	0.13	-0.12	0.39	0.71	0.06	0.47	0.45	0.41	1.00	-0.19	0.03	-0.21
Zr	-0.04	0.35	-0.17	-0.16	0.42	-0.25	-0.32	-0.10	-0.19	1.00	-0.22	0.01
Mag. Sus	0.01	-0.42	0.16	0.05	-0.18	0.29	0.30	0.17	0.03	-0.22	1.00	-0.18
Mo. Ratio	-0.06	0.07	-0.07	-0.15	0.02	-0.23	-0.12	-0.03	-0.21	0.01	-0.18	1.00

9.8 Appendix 8 – Calibration of ITRAX and pXRF

Old Boo Core 1

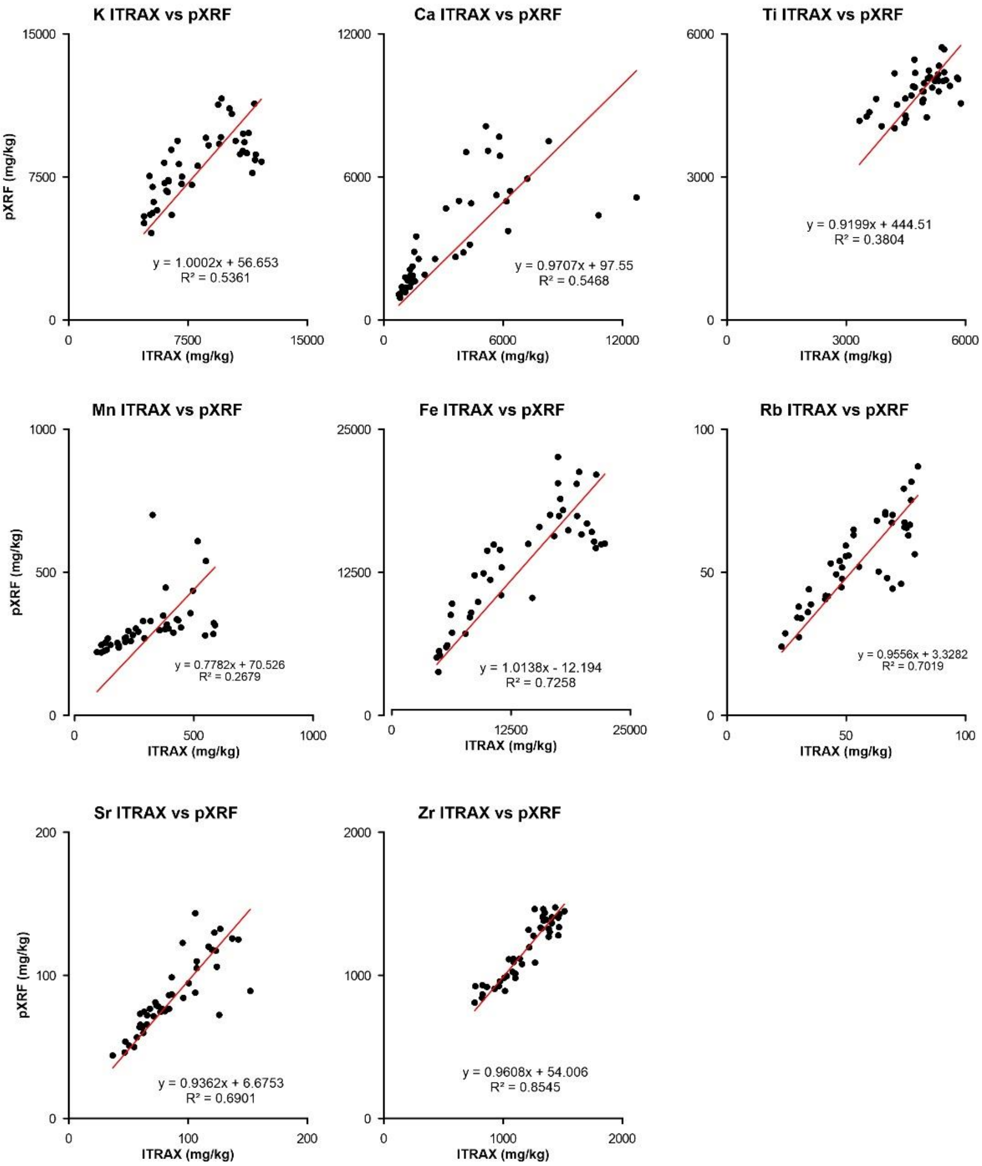

Figure 9.5: *Comparison of results from CPS in ITRAX and Mg/kg for pXRF showing linear regressions.*

9.9 Appendix 9 Dating

Table 9.12: *Summary table of Radiocarbon results for cores 1,2 and 3 from Old Boo*

Sample ID	Combustion			$\delta^{13}C$ (‰)	^{14}C Age (BP)		Calibrated age (cal BP)				
	Sample (mg)	C (mg)	C content (%)		Mean	1σ	1σ range		2σ range		Median
PW2-C1 20-25 cm	232.86	0.27	0.12	-24.7	2385	40	2434	2323	2681	2205	2370
PW2-C1 40-45 cm	262.39	0.17	0.06	-25.0*	5945	50	6785	6665	6884	6567	6725
PW2-C2 20-25 cm	196.72	0.13039	0.07	-25.9	7560	60	8398	8215	8415	8191	8331
PW2-C2 40-45 cm	500.95	0.08915	0.02	-24.2	12290	130	14515	13960	14825	13773	14232
PW2-C3 20-25 cm	183.68	0.23	0.13	-24.9	2150	40	2148	2018	2303	1998	2089
PW2-C3 45-50 cm	695.06	0.10699	0.02	-25.8	15150	100	18510	18229	18616	18066	18359

Table 9.13: *Summary table of $^{210}Pb_{ex}$ results.*

Depth (cm)	Total ^{210}Pb (Bq/kg)	Supported ^{210}Pb (Bq/kg)	Uncorrected Unsupported ^{210}Pb (Bq/kg)	Unsupported 210Pb Decay corrected to 24-Aug-15 (Bq/kg)	Mid depth (cm)	Calculated CIC Ages (years)	Calculated CRS Ages (years)	CRS model Mass Accumulation Rates ($g/cm^2/year$)
0-2	53.1 ± 2.1	4.9 ± 0.5	48.2 ± 2.1	48.2 ± 2.1	1	14 ± 14	12 ± 3	0.09 ± 0.01
2-4	25.8 ± 1.0	5.5 ± 0.5	20.3 ± 1.2	20.3 ± 1.2	3	42 ± 14	33 ± 6	0.11 ± 0.01
4-6	15.9 ± 0.7	6.5 ± 0.6	9.5 ± 1.0	9.5 ± 1.0	5	66 ± 13	49 ± 7	0.15 ± 0.02
6-8	11.5 ± 0.5	5.5 ± 0.5	6.0 ± 0.7	6.0 ± 0.7	7	76 ± 13	62 ± 8	0.15 ± 0.03
8-10	11.5 ± 0.5	6.6 ± 0.6	4.8 ± 0.8	4.8 ± 0.8	9	86 ± 14	78 ± 9	0.12 ± 0.03
10-12	10.3 ± 0.5	6.5 ± 0.6	3.8 ± 0.8	3.8 ± 0.8	11	95 ± 14	98 ± 10	0.08 ± 0.03
12-14	10.4 ± 0.5	4.7 ± 0.5	5.7 ± 0.7	5.7 ± 0.7				
14-16	10.3 ± 0.5	5.0 ± 0.5	5.3 ± 0.7	5.3 ± 0.7				
16-18	9.7 ± 0.5	5.7 ± 0.5	4.1 ± 0.7	4.1 ± 0.7				
18-20	9.7 ± 0.5	6.0 ± 0.5	3.7 ± 0.7	3.7 ± 0.7				

Table 9.14: *Bulk Density and Moisture Content of the sediment used for ^{210}Pb analysis.*

Sample Depth (cm)	Mass of beaker+ dried sample (g)	Mass of total wet sample (g)	Mass of total dry sample (g)	Moisture content (%)	Wet mass in meas. Cyl (g)	Dry mass in meas. Cyl (g)	Dry bulk density (g/mL)
0 to 2	45.27	15.51	12.51	19.34	2.75	2.22	1.11
2 to 4	63.42	16.95	13.99	17.44	2.58	2.13	1.07
4 to 6	57.91	16.79	14.14	15.80	2.13	1.79	0.90
6 to 8	63.20	19.87	16.09	19.02	2.95	2.39	1.19
8 to 10	67.30	16.99	14.01	17.56	2.26	1.86	0.93
10 to 12	61.91	19.38	15.99	17.46	2.39	1.97	0.99
12 to 14	55.62	18.16	14.74	18.83	2.38	1.93	0.97
14 to 16	54.32	14.11	10.88	22.91	2.52	1.94	0.97
16 to 18	66.66	14.24	11.14	21.74	2.54	1.99	0.99
18 to 20	60.11	18.50	15.20	17.83	2.58	2.12	1.06

9.10 Appendix 10 – Wetland Ecology

Table 9.15: *Presence (1) or absence (0) of biological remains in Old Boo Core 1 (Data provided by Dr Yoshi Kobayashi).*

1: present; 0: absent			Aquatic plants		Aquatic animals			
Wetland	**Core**	**Depth (cm)**	**Diatoms**	**Charophytes (as oospores)**	**Freshwater sponges (as spicules)**	**Chiromomids (as head capsules)**	**Bivalves**	**Cladocerans (as head shields)**
PW2	C1-1	0-2	1	1	1	1	1	0
PW2	C1-1	2-4	1	1	1	0	0	1
PW2	C1-1	4-6	0	1	1	0	0	0
PW2	C1-1	6-8	0	1	1	0	0	0
PW2	C1-1	8-10	0	1	1	0	0	0
PW2	C1-1	10-12	0	1	1	0	0	0
PW2	C1-1	12-14	0	1	1	0	0	0
PW2	C1-1	14-16	1	1	0	0	0	0
PW2	C1-1	16-18	1	1	1	0	0	0
PW2	C1-1	18-20	1	1	1	0	0	0
PW2	C1-1	20-22	1	1	1	0	0	0
PW2	C1-1	22-24	1	1	1	0	0	0
PW2	C1-1	24-26	1	1	1	0	0	0
PW2	C1-1	26-28	0	1	1	0	0	0
PW2	C1-1	28-30	0	1	1	0	0	0
PW2	C1-1	30-32	0	0	1	0	0	0
PW2	C1-1	32-34	0	1	1	0	0	0
PW2	C1-1	34-36	0	0	1	0	0	0
PW2	C1-1	36-38	0	0	1	0	0	0
PW2	C1-1	38-40	0	0	1	0	0	0
PW2	C1-1	40-42	0	0	1	0	0	0
PW2	C1-1	42-44	0	0	1	0	0	0
PW2	C1-1	44-47	0	0	1	0	0	0
PW2	C1-1	47-51	0	0	1	0	0	0
PW2	C1-2	51-53	0	0	1	0	0	0
PW2	C1-2	53-55	0	0	1	0	0	0
PW2	C1-2	55-57	0	0	1	0	0	0
PW2	C1-2	57-59	0	0	1	0	0	0
PW2	C1-2	59-61	0	0	1	0	0	0
PW2	C1-2	61-63	0	0	1	0	0	0
PW2	C1-2	63-65	0	0	1	0	0	0
PW2	C1-2	65-67	0	0	1	0	0	0
PW2	C1-2	67-69	0	0	1	0	0	0
PW2	C1-2	69-71	0	0	1	0	0	0
PW2	C1-2	71-73	0	0	1	0	0	0
PW2	C1-2	73-75	0	0	1	0	0	0
PW2	C1-2	75-77	0	0	1	0	0	0
PW2	C1-2	77-79	0	0	1	0	0	0
PW2	C1-2	79-81	0	0	1	0	0	0
PW2	C1-2	81-83	0	0	1	0	0	0
PW2	C1-2	83-85	0	0	0	0	0	0
PW2	C1-2	85-87	0	0	0	0	0	0
PW2	C1-2	87-89	0	0	0	0	0	0
PW2	C1-2	89-91	0	0	0	0	0	0
PW2	C1-2	91-93	0	0	1	0	0	0
PW2	C1-2	93-95	0	0	0	0	0	0

9.11 Appendix 11 – Photomicrographs

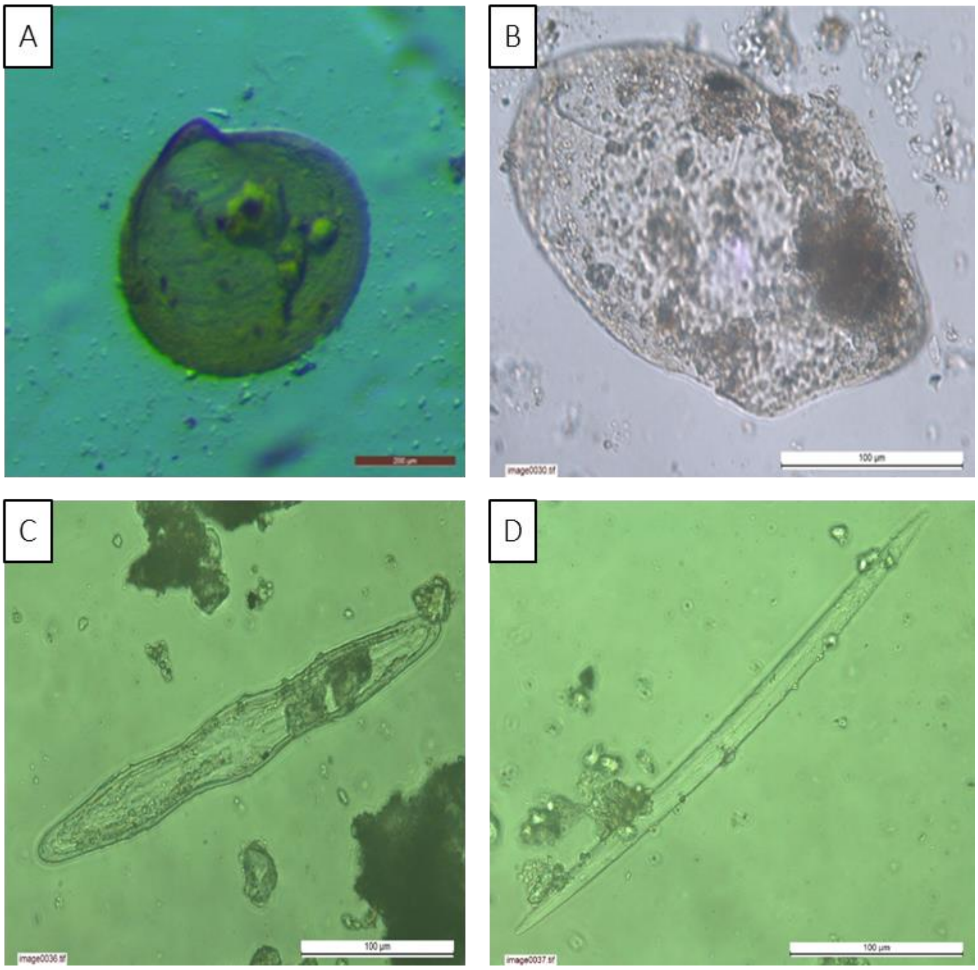

Figure 9.6: *Photomicrographs of biological remains and the depths found for **(A)** Bivalve 0-2 cm; **(B)** Cladoceran head shield 0-2 cm; **(C)** Diatom Pinnularia 24-26 cm and **(D)** Freshwater Sponge Spicule 34-36 cm.*