Title: Establishing carbon retention and sequestration in a submerged mangrove using isotope analysis

Author: Jane Curran

Year: 2015

Repository DOI:

2015

Establishing carbon retention and sequestration in a submerged mangove using isotope analysis

Jane Curran
University of Wollongong

Establishing carbon retention and sequestration in a submerged mangove using isotope analysis

Abstract

Carbon sinks are recognised as an important environmental commodity, however are often assumed to be stable. Climate change, and in particular sea-level rise may alter the stability of coastal carbon sinks. Mangrove and saltmarsh are amongst the most efficient ecosystems at sequestering carbon; however the effect of sea-level rise on sediment accretion and carbon accumulation, and its subsequent effect on carbon sequestration and carbon retention remain unknown. This study uses a range of isotopic techniques, including

^{210}Pb-dating techniques to determine a core sediment chronology, and stable carbon isotope analyse, to determine the effect of rapid sea-level rise on the sources of carbon in a coastal carbon sink. The study site, located at Chain Valley Bay, Lake Macquarie, underwent rapid submergence following the collapse of a long wall mine in the mid-1980s; and this submergence was used as a surrogate for exploring the effects of rapid sea-level rise on a coastal carbon sink. Temporal mapping of vegetation distribution highlighted the dieback of vegetation and subsequent recovery of vegetation following submergence; however areas in the lower intertidal zone remained permanently inundated. The permanently submerged wetland area had a higher accretion rate following submergence than the recovery area that is now vegetated with mangrove. The wetland has attempted to keep up with water level rise and as a result carbon sequestration increased in the submerged area from 300.0 g C m^{-2} yr^{-1} to 627.3 g C m^{-2} yr^{-1}, and the mangrove area increased slightly from 56 g C m^{-2} yr^{-1} to 68 g C m^{-2} yr^{-1}. Both zones had an increase in sediment mass, indicating a shift in sediment sources to more mineral based following inundation. Carbon isotope analyses reflected the changes in sediment sources in each zone. Isotopic values showed an obvious shift from marine sourced material to terrestrial material up the core and is indicated by the depletion of δ^{13}C (values from -30‰ to -11.7‰). Sediment characteristics and carbon store indicate central mud basin sediments within lower cores due to the dominance of muds and silts and lower carbon store and fluvial delta sediments located middle core contained more recalcitrant carbon and larger grains sizes with significant gravel components. In the upper core there was a shift to high density of carbon. The amount of carbon is more in mangrove and mixed forest vegetation than saltmarsh. These results suggest that where hydrodynamic conditions are suitable and sediment supply is sufficient, coastal carbon sinks following sea-level rise will not become net carbon emitters but may increase their carbon storage capacity.

Degree Type

Thesis

Degree Name

Bachelor of Science (Honours)

Department

School of Earth & Environmental Sciences

Advisor(s)

Kerrylee Rogers

Keywords

relative sea-level rise, vulnerability, blue carbon mine subsidence, Lkae Macquarie, carbon sinks

Department of Earth and Environmental Science

Establishing carbon retention and sequestration in a submerged mangrove using isotope analysis

By

Jane Curran

"This thesis is presented as part of the requirements for the award of the Degree of Bachelor of Science (Honours) University of Wollongong"

April 2015

The information in this thesis is entirely the result of investigations conducted by the author, unless otherwise acknowledged, and has not been submitted in part, or otherwise, for any other degree or qualification.

Jane Curran

8th April 2015

ACKNOWLEDGEMENTS

I wish to acknowledge the help and support provided to me throughout my honours year and hopefully convey the vast appreciation I have for them.

Firstly, I would like to thank my supervisor Kerrylee Rogers for her unfailing support and willingness to help me with my project and always having an open door.

Thanks goes to the staff within the Environmental Resources Department at ANSTO. Atun Zawadzki and Jack Goralewski who shared with me there vast knowledge of radiometric dating and allowed me to use their labs. Scott and Barbora who made pelletising more than bearable and Debashish Mazumder who was always available to help and provided me with a warm welcome to ANSTO.

A big thank you to the field sampling team Chris Owers, Kirti Lal, Josef Blackley-Stocker and Kerrylee Rogers. Even though it was muddy wet work and octopuses were abound you made it go smoothly.

Thank you also to the Earth and Environmental Department for providing lab space and equipment and to honours coordinators Sol Buckman and Marina McGlinn.

Finally, thank you to my friends and family who have given me much need distractions from honours and Carole Vela for helping with editing.

ABSTRACT

Carbon sinks are recognised as an important environmental commodity, however are often assumed to be stable. Climate change, and in particular sea-level rise may alter the stability of coastal carbon sinks. Mangrove and saltmarsh are amongst the most efficient ecosystems at sequestering carbon; however the effect of sea-level rise on sediment accretion and carbon accumulation, and its subsequent effect on carbon sequestration and carbon retention remain unknown. This study uses a range of isotopic techniques, including ^{210}Pb-dating techniques to determine a core sediment chronology, and stable carbon isotope analyse, to determine the effect of rapid sea-level rise on the sources of carbon in a coastal carbon sink. The study site, located at Chain Valley Bay, Lake Macquarie, underwent rapid submergence following the collapse of a long wall mine in the mid-1980s; and this submergence was used as a surrogate for exploring the effects of rapid sea-level rise on a coastal carbon sink. Temporal mapping of vegetation distribution highlighted the dieback of vegetation and subsequent recovery of vegetation following submergence; however areas in the lower intertidal zone remained permanently inundated. The permanently submerged wetland area had a higher accretion rate following submergence than the recovery area that is now vegetated with mangrove. The wetland has attempted to keep up with water level rise and as a result carbon sequestration increased in the submerged area from 300.0 g C m^{-2} yr^{-1} to 627.3 g C m^{-2} yr^{-1}, and the mangrove area increased slightly from 56 g C m^{-2} yr^{-1} to 68 g C m^{-2} yr^{-1}. Both zones had an increase in sediment mass, indicating a shift in sediment sources to more mineral based following inundation. Carbon isotope analyses reflected the changes in sediment sources in each zone. Isotopic values showed an obvious shift from marine sourced material to terrestrial material up the core and is indicated by the depletion of δ^{13}C (values from -30‰ to -11.7‰). Sediment characteristics and carbon store indicate central mud basin sediments within lower cores due to the dominance of muds and silts and lower carbon store and fluvial delta sediments located middle core contained more recalcitrant carbon and larger grains sizes with significant gravel components. In the upper core there was a shift to high density of carbon. The amount of carbon is more in mangrove and mixed forest vegetation than saltmarsh. These results suggest that where hydrodynamic conditions are suitable and sediment supply is sufficient, coastal carbon sinks following sea-level rise will not become net carbon emitters but may increase their carbon storage capacity.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS iii
ABSTRACT iv
TABLE OF CONTENTS v
LIST OF FIGURES vii
LIST OF TABLES xi
LIST OF ABBREVIATIONS 12
1. INTRODUCTION 13
2. LITRATURE REVIEW 17
1.1 Background 17
1.2 Ecosystem Services 17
1.3 Wetland response to sea level rise 22
1.4 South-East Australian Wetlands 25
1.5 Carbon Accretion 27
1.6 Capacity to store and sequester carbon 29
3. REGIONAL SETTING 30
1.7 Study site location 30
1.8 Industrial activity at Lake Macquarie 31
1.9 Coastal geomorphology and estuarine dynamics 34
1.10 Climate 36
1.11 Tides 37
1.12 Winds and waves 38
1.13 Ecology 39
1.14 Chapter Summary 40
4. METHODOLOGY 41
1.15 Spatial Analysis 41
1.15.1 Vegetation Change mapping 41
1.15.2 Ground Truthing 43
1.16 Wetland Morphology 43
1.16.1 Digital Elevation Model 43

1.16.2 RTK-GPS positioning 44
1.16.3 Bathymetry 45
1.17 Accretion and Carbon Store 46
1.17.1 Sample Collection 46
1.17.2 Vertical Accretion 50
1.17.3 Sediment Characteristics 54
1.17.4 Carbon dynamics and sources 56
1.18 Chapter Summary 58
5. RESULTS 60
1.19 Vegetation Dynamics 60
1.20 Wetland morphodynamics 75
1.20.1 Digital elevation model (DEM) 75
1.20.2 Bathymetry 78
1.21 Vertical Accretion 80
1.21.1 Accretion and Carbon Storage 80
1.21.2 Mass Accumulation 81
1.22 Sediment Characteristics and Carbon Storage 83
1.22.1 Carbon Sources 90
1.22.2 Carbon Dynamics 92
1.23 Chapter Summary 93
6. DISCUSSION 95
1.24 Vegetation characteristics 95
1.25 Wetland morphology 96
1.26 Carbon Accretion 96
1.27 Changes in carbon sources 98
1.28 Implications of sea-level rise 99
1.29 Limitations 99
1.30 Chapter Summary 100
7. CONCLUSIONS AND RECOMMENDATIONS 101
1.31 Conclusions 101
1.32 Recommendations 102
REFERENCES 104
APPENDIX A – Radiometric isotope Lead-210 report. 111

APPENDIX B – Carbon isotope resluts provided by ANSTO......112

LIST OF FIGURES

Figure 2-1 A comparison of the mean carbon storage in the above and belowground biomass within terrestrial forests and coastal vegetation ecosystems (Fourqurean et al., 2014b)......19

Figure 2-2 Mean long-term rates of carbon sequestration (g C m^{-2} yr^{-1}) within terrestrial forests and vegetated coastal ecosystems. Error bars indicate maximum rates of accumulation (McLeod et al., 2011). 20

Figure 2-3Global mean sea level rise predicted using values from 1986 to 2005. An obvious trend of increasing sea level is seen (IPCC, 2014)......21

Figure 2-4 the global carbon cycle based on the 1990 decade. Natural fluxes are shown in black and anthropogenic in red. Wetlands specifically shown are not shown, but they are contributors to carbon stores and sequestration through vegetation and soil mediums (Solomon, 2007)......22

Figure 2-5 Major components of the carbon cycle surrounding vegetation and the pathways including respiration and fermentation causing CO2 to form. In a wetland, organic carbon is converted to CO2 and methane and/or stored in plants, dead plant matter, microorganisms, or peat (Kayranli, 2010). 22

Figure 2-6 Estimated gains and losses of carbon (C) from different coastal processes in the Mississippi Delta (DeLaune and White, 2012)......23

Figure 2-7 Salt marsh organic content accretion and loss due to subsidence, Mississippi Delta, USA (DeLaune and White, 2012)......24

Figure 2-8 Morphodynamic feedback on sedimentation in mangrove ecosystems (Masselink and Gehrels, 2014)......25

Figure 2-9 Claystone roof and floor failure likely seen at Chain Valley Bay causing subsidence of the Wetland (Mcnally, 2014). 27

Figure 2-10 A schematic diagram of the movement of supported and unsupported daughter isotope ^{210}Pb into the sediments from the atmosphere, erosional material and in-wash (Oldfield and Appleby, 1984)......28

Figure 2-11 The distribution of δ ^{13}C values of plant material where values approximately -14‰ are C_3 plants and values approximately -28‰ are C_4 plants (O'Leary 1988)......29

Figure 3-1 The study location Chain Valley Bay in its wider context on the New South Wales central coast and the wetland in 2014 (Basemap source: Esri, DigitalGlobe, GEOEye, i-cubed, Earthstar, Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community. 2014 aerial map source: Wyong Shire Council)....30
Figure 3-2 Coalfields within the Sydney Basin, NSW. Lake Macquarie is located in the Newcastle Coalfield (NSW Dept TIRE)....31
Figure 3-3 Local stratigraphy at Chain Valley Bay Colliery (diagram based on one by LakeCoal, 2013). Wallarah, Great Northern and Fassifern coal seams have been mined at the Chain Valley Colliery....32
Figure 3-4 Approximate locations of collieries, mines and power stations surrounding the study site and Lake Macquarie (Base map source: Esri, DigitalGlobe, GEOEye, i-cubed, Earthstar, Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community. 2014 aerial map source: Wyong Shire Council)....34
Figure 3-5 Stage A or youthful stage of infilling in a barrier estuary like Lake Macquarie (Roy et al., 2001). The tidal range is smaller than evolutionary stages B, C and D....36
Figure 3-6 Changes in surface area of different depositional environments in the transition of an estuary from youthful to mature (Roy et al., 2001). *Note: COE = Cut-off embayment's.* 36
Figure 3-7 The Wave orbital motions within Lake Macquarie that is currently unfilled. The lake is deeper than the threshold depth due to low sediment supply (Adlam, 2014)....39
Figure 4-1 Real Time Kinematic (RTK) positioned to collect xyz data at Chain Valley Bay, Lake Macquarie for the purpose of obtaining geographic positions and elevations at core locations. 45
Figure 4-2 Chain Valley Bay Wetland distribution of mangrove, saltmarsh mixed forest and submerged vegetation in 2014. This map was used for plotting core locations. 46
Figure 4-3 Core locations at Chain Valley Bay and transects 1 and 2 of which cores were collected along on the 8th and 9th September 2014....47
Figure 4-4 a) The A frame pully system of removing sediment cores used at Chain Valley Bay. The tripod is launched off the boat and the core is hammered into the ground and a suction plug is added to the top before being pulled up. b) The core removal technique used on land at Chain Valley Bay. The core is hammered into the ground and the suction plug is added to the top of the core before a clamp is attached and the core is gradually wiggled out. c) Cores were cut open on site and subsampled before being placed directly in a 3-5ºC cold storage box. 48

Figure 4-5 (a) Top 30cm of the mangrove core sliced every 1cm and dried in a 60 ºC oven, (b) and the core samples just taken out of the oven and ready to be bagged and labelled to take to ANSTO. 51
Figure 5-1 Aerial photography and spatial vegetation mapping of the Chain Valley Bay wetland in 1984......61
Figure 5-2 Aerial photography and spatial vegetation mapping of the Chain Valley Bay wetland in 1986......61
Figure 5-3 Aerial photography and spatial vegetation mapping of the Chain Valley Bay wetland in 1990......63
Figure 5-4 Aerial photography and spatial vegetation mapping of the Chain Valley Bay wetland in 1987......63
Figure 5-5 Aerial photography and spatial vegetation mapping of the Chain Valley Bay wetland in 1996......65
Figure 5-6 Aerial photography and spatial vegetation mapping of the Chain Valley Bay wetland in 2003......65
Figure 5-7 Aerial photography and spatial vegetation mapping of the Chain Valley Bay wetland in 2006......67
Figure 5-8 Aerial photography and spatial vegetation mapping of the Chain Valley Bay wetland in 2010......67
Figure 5-9 *Avicennia marina m*angrove seedlings growing on the edge of the current mangrove area within gaps. 68
Figure 5-10 Aerial photography and spatial vegetation mapping of the Chain Valley Bay wetland in 2014......69
Figure 5-11 Vegetation area change (m^2) in the Chain Valley bay wetland from before inundation to 2014......70
Figure 5-12 DEM of the Chain Valley Bay wetland derived using Lidar data collected in 2007. 75
Figure 5-13 Elevation (m) of vegetation zones through time derived using a DEM created using Lidar collected in 2007. 76
Figure 5-14 Bathymetry at Chain Valley Bay (contour interval 0.25 m). Remnant wetland is evident from before the mine collapse. 79
Figure 5-15 Accretion (mm y^{-1}) (±SD) at Chain Valley Bay within mangrove and submerged areas calculated use ^{210}Pb radiometric isotopes. 81

Figure 5-16 Mass Accumulation (g cm^{-2} y^{-1}) (±SD) at Chain Valley Bay within mangrove and submerged areas calculated use ^{210}Pb radiometric isotopes..82
Figure 5-17 Submerged core 1A located in the submerged section of the wetland located at the front...84
Figure 5-18 Submerged core 2A located in the submerged section of the wetland located at the front...84
Figure 5-19 Mangrove core 1B located in the mangrove section of the wetland on transect 1.........85
Figure 5-20 Mangrove core 2B located in the mangrove section of the wetland on transect 2.........86
Figure 5-21 Saltmarsh core 1C located in the salt marsh area of the wetland within transect 1. 87
Figure 5-22 Saltmarsh core 2C located in the salt marsh area of the wetland within transect 2. 87
Figure 5-23 Core 1D located in the mixed forest zone of the wetland in transect 1..........................88
Figure 5-24 Core 2D located in the mixed forest zone of the wetland in transect 2..........................89
Figure 5-25 Core E located in the mixed forest zone of the wetland between transects 1 and 2 and is the furthest landward core...89
Figure 5-26 Carbon values (±SD) in each vegetation zone of the Chain Valley Bay wetland determined using bulk density and % carbon information. Mixed forest and mangrove appear to be storing the most carbon...93

LIST OF TABLES

Table 4-1 The assigned labels to each core within Chain Valley Bay and the vegetation zone and transect they are located within. 49

Table 4-2 Marine and Terrestrial carbon sources possible at Chain Valley Bay and their carbon 13 isotopic signature and vegetation classification. 58

Table 5-1 Vegetation change and rate of change through time for available time periods. 71

Table 5-2 Photographs taken on the 18th December 2014 (a) showing remnant dead tree trunks previously of the mixed forest but now within saltmarsh (b) left- remnant dead tree trunks in the submerged area of the mangrove at the front of the wetland, right- small Casuarina trees within the mixed forest zone with a species of wetland grass underneath. (c) mangrove areas previously populated by paperbark trees (*Melaleuca quinquenervia*) which only exist now as dead tree trunks. 72

Table 5-3 Vegetation zonation change through due to rapid inundation. 74

Table 5-4 Average elevation values were created based on RTK and DEM 2007 elevations and mean elevation defined for the period between 2007 and 2014. 77

Table 5-5 Transition point between changes in bulk density, % carbon, isotopic signatures and sediment characteristics. 92

LIST OF ABBREVIATIONS

ML	Mega litres
Km^2	Kilometres Squared
m	Metres
cm	Centimetres
mm	Millimetres
$g\ cm^{-3}$	Grams per centimetre cubed
$mm\ y^{-1}$	Millimetres per year
$g\ C\ m^{-2}\ yr^{-1}$	Grams of carbon per metre squared per year
NSW	New South Wales
DEM	Digital Elevation Model
TIN	Triangulated Irregular Network
Lidar	Light Detection and Ranging
GPS	Global Positioning System
RMSE	Root Mean Square Error
RTK	Real Time Kinematic

1. INTRODUCTION

Coastal wetlands are low-energy environments within the coastal zone, and more specifically, found within an elevation that ranges between sub-tidal depths and the landward edge where the sea passes its hydrological influence to groundwater and atmospheric processes (Wollanski et al., 2009). Wetlands provide numerous ecosystem services including biological productivity and diversity, coastal protection, erosion control, water purification, maintenance of fishers and carbon sequestration (Barbier et al., 2011). They are increasingly being recognised for their ability to help mitigate climate change by acting as buffers to inundating floodwaters and acting as blue carbon sinks and sequestering large amounts of carbon from the atmosphere and oceans (McLeod et al., 2011). Blue carbon is carbon stored from marine ecosystems. Blue carbon within wetland vegetation is stored within the soil, the living biomass aboveground and belowground and the non-living biomass (Howard et al., 2014). Unlike terrestrial forest carbon stores, carbon sequestered in coastal soils can be extensive and remain trapped for centuries to millennia (Brevik and Homburg, 2004). Mangroves and saltmarshes are thought to release negligible amounts of greenhouse gases and have a unique ability to store more carbon per unit area than terrestrial forests (Chmura et al., 2003). Mangrove and saltmarsh ability to store large amounts of carbon have been documented for 154 sites globally in literature by Chmura et al., (2003) and are thought to store at least 44.6 Tg C yr^{-1} and probably more.

The effect of rapid sea level rise on wetland vegetation sequestration ability and the fate of carbon is little understood, and will depend on the response of vegetated shorelines to sea-level rise and the fate of stored carbon following submergence (Choi and Wang, 2001; Mcleod et al., 2011). Losses in carbon stored within wetlands has been related to sea-level rise, sediment accumulation, subsidence, storm events, rate of wetland loss and coastal restoration (DeLaune and White, 2012). Carbon can be released from wetlands through erosion and dispersion of sediments enabling faster breakdown and conversion to greenhouse gases. The available greenhouse gases can be released into the ocean and back into the atmosphere and contribute to ocean acidification and greenhouse gases (Nellemann et al., 2009). Ocean acidification can cause a large reduction in the ability of the ocean to absorb atmospheric CO_2 and marine ecosystems are expected to be severely affected due to calcium carbonate saturation levels within the ocean reducing.

Research has addressed the driving processes and controls of carbon dynamics in coastal systems but less emphasis has been place on how anthropogenic influences and sea level rise may affect the carbon stored within vegetated systems (McLeod et al., 2011). The role of humans in the reduction of blue carbon sinks due to disturbances like clearing, dredging and filling is revealing large losses in vegetation is occurring that would be having impacts on carbon sequestration and carbon stored in coastal systems.

A global loss in blue carbon sinks is already being observed with estimates of 30-50% mangrove lost since the 1940s, 50% seagrass lost since the 1990s and 25% saltmarsh lost since the 1800s (McLeod et al., 2011). Research on vegetated coastal ecosystems is needed to determine the combined effects of climate change, land-use practices and human impacts like pollution and eutrophication on the sequestration of Carbon (McLeod et al, 2001).

Recent research proposes coastal wetlands may become net carbon emitters following submergence due to a collapse in peat with plant mortality and the erosion of soils due to increasing wave energy (DeLaune et al., 1994; DeLaune and White, 2012; Kirwan and Mudd 2012). This concept has not been fully tested and has only occurred within coastal areas that suffer high energy events like hurricanes. Carbon sequestration studies in coastal environments that are relatively sheltered with low wave energy needs to be conducted to understand if these environments would also be net emitters or would keep up with sea level rise and continue to sequester carbon.

A coastal wetland at Chain Valley Bay, Lake Macquarie, was impacted by subsidence of 0.85 m since 1987 due to a the removal of pillars from the underlying mine (MSB, 1991). This subsidence provides a unique opportunity to explore the consequences of accelerated sea-level rise on sediments and carbon stored in coastal wetlands. The Lake Macquarie estuary is located on south east Australia and is a low energy environment.

This study investigated the fate of carbon and sediments using recent inundation as a surrogate for sea-level rise within the Chain Valley Bay wetland. The study objectives are as follows:

1. Undertake temporal mapping of vegetation distribution to determine the fate of vegetation following sea-level rise.
2. Determine the effect of sea-level rise on sediment accretion and carbon accumulation using ^{210}Pb isotope techniques.

3. Characterise sediments in different vegetation zones and identify any fluctuations with depth.
4. Undertake stable carbon isotope analysis to determine the effect of rapid sea-level rise on carbon sequestration and carbon retention.

Estimates of carbon stock and rates of accumulation have been conducted on sediment cores and rates of carbon accumulation has been estimated using dating techniques (Chmura et al., 2003). Radiocarbon dating of bulk peat from high marsh soils within north-west Florida were used in conjunction with carbon isotopic analysis to indicate the period of change between dominant species as a result of accelerated sae level rise over the last century (Choi et al., 2001). This study uses both radiometric dating techniques and carbon isotopic analysis on sediments to determine the fate of carbon following rapid submergence and isotopic signatures within sediments to identify the sources of carbon before and after inundation. In addition vertical accretion and mass accumulation analysis of sediments was undertaken in submerged and mangrove areas to quantify the carbon sequestration within wetlands suffering rapid inundation which is used as a surrogate to predict changes due to rapid sea level rise.

Vegetation succession due to sea level rise has become a priority in the management of coastal environments. Mangrove, saltmarsh and *Casuarina* vegetation located on south east Australia have been mapped using spatial analyst tools and predictions of vegetation zonation due to different sea level rise scenarios modelled (Rogers et al., 2006; Oliver et al., 2012). Using historical aerial photography this study had the unique opportunity to map vegetation change following rapid inundation. Digital terrain modelling and bathymetry data are also used to indicate changes in elevation following subsidence and to show the morphodynamic characteristics of the wetland following submergence.

The variety of analysis and approaches undertaken in this study are presented in chapters. Chapter 2 is a literature review and provides a background on wetlands and coastal systems, information on ecosystem services provided by wetlands, a characterisation of South East Australian wetlands. It also provides background on techniques used for determining carbon accretion, carbon store and sequestration. Chapter 3 is the regional setting of the study site including industrial activity, coastal geomorphology, climate, tides, winds and waves and ecology. Chapter 4 is the methodology used within this study and details spatial analysis techniques, wetland morphology methods and methods for determining accretion and carbon store. Chapter 5 are results including vegetation dynamics, wetland morphology, vertical accretion, sediment characteristics and carbon storage. Following this chapter 6 is a discussion of results and is presented in order of vegetation characteristics, wetland morphology, carbon accretion, changes in carbon sources, implications of sea level rise and limitations. Chapter 7 includes conclusions and recommendations for future studies. Chapters 3, 4, 5 and 6 have summaries at the end of the chapter.

2. LITRATURE REVIEW

1.1 Background

It is becoming increasingly necessary to explain the geomorphic changes that are occurring within the coastal zone around the world for the management of coastal resources by the global community now and in the future. Recent studies into climate change have shown evidence of increasing sea-level around Australia consistent with the global mean, within the past 50 years (White et al., 2014).

A broad definition of the coastal zone is the area between the seaward limit of terrestrial influence and the landward limit of marine influence (Haslett, 2000). This definition changes within individual coastal settings where coastal dynamics such as sediment supply and wave energy can cause different morphodynamics within estuaries (Roy et al., 2001). Wetlands are within the coastal zone, and more specifically, found within an elevation that ranges between sub-tidal depths and the landward edge where the sea passes its hydrological influence to groundwater and atmospheric processes (Wollanski et al., 2009). Within this region light should be able to penetrate and support photosynthesis of benthic plants such as seagrass (Wollanski et al., 2009). At their seaward margin wetlands can be represented by microfauna including biofilms, benthic algae and vegetation such as seagrass. At the landward margin vegetation boundaries can range from occurrences on groundwater seeps, fens in humid climates to relatively barren salt flats in arid climates (Wollanski et al., 2009). The geomorphic setting of wetlands greatly influences the ecology of many coastal zones.

1.2 Ecosystem Services

The ecological significance of mudflats, saltmarshes and mangroves that occur in many wetland areas is important for two reasons. Wetland ecological areas are productive ecosystems and contribute to the near shore food web. Wetlands are able to provide habitats and perform nursery role for a wide range of species including those that have a high rate of primary productivity (Woodroffe, 2003). They are also able to provide a record of changing environments due to their preservation of fine sediments. The coastal stratigraphic record is a form of archive and allows us to examine rates and directions of changes in the past and provide analogies for future changes, particularly in response to human influences and future sea levels (Woodroffe, 2003).

Between 1750 and 2011 cumulative CO_2 emissions to the atmosphere were 2040 ± 310 $GtCO_2$ and about 40% has remained in the atmosphere The remaining CO_2 has been stored on land and in the oceans and ocean acidification has occurred as a result from the over absorption of CO_2 since the beginning of the industrial era (IPCC, 2014). Anthropogenic greenhouse gas emissions have continued to increase between 2000 and 2010 despite the increasing awareness and mitigation policies being implemented and has thought to be in part due to in part to the economic growth in this period (IPCC, 2014). The importance of coastal ecosystems in the future climate scenario if similar trends are to follow become increasingly clear.

Coastal wetland areas dominated by wetland vegetation such as mangroves, saltmarshes and seagrasses and act as carbon sinks. These environments have recently been termed blue carbon sinks and provide efficient areas for the storage of large amounts of carbon per unit area and are thought to release negligible amounts of greenhouse gases (Chmura et al., 2003). When compared to terrestrial carbon stores, mangrove, saltmarsh and seagrass vegetation is more extensive in predominantly in soil organic carbon (SOC) (Figure 2-1). Mangroves are the most productive carbon storage vegetation in both SOC and living biomass compared to Boral forest, tropical forest, seagrass and saltmarsh. Blue carbon within wetland vegetation is stored within the soil, the living biomass aboveground and belowground and the non-living biomass (Howard et al., 2014). These blue carbon areas play an important role in the global sequestration of carbon that is within the atmosphere and oceans (McLeod et al., 2011). A unique ability of coastal carbon sinks is the extensive amount of carbon that can remain trapped for long periods of time (Duarte et al., 2005). Recent and predicted sea level rise has caused many people to wonder what would happen to the vast carbon stores within blue carbon sinks and if they would they start to erode and become net carbon emitters.

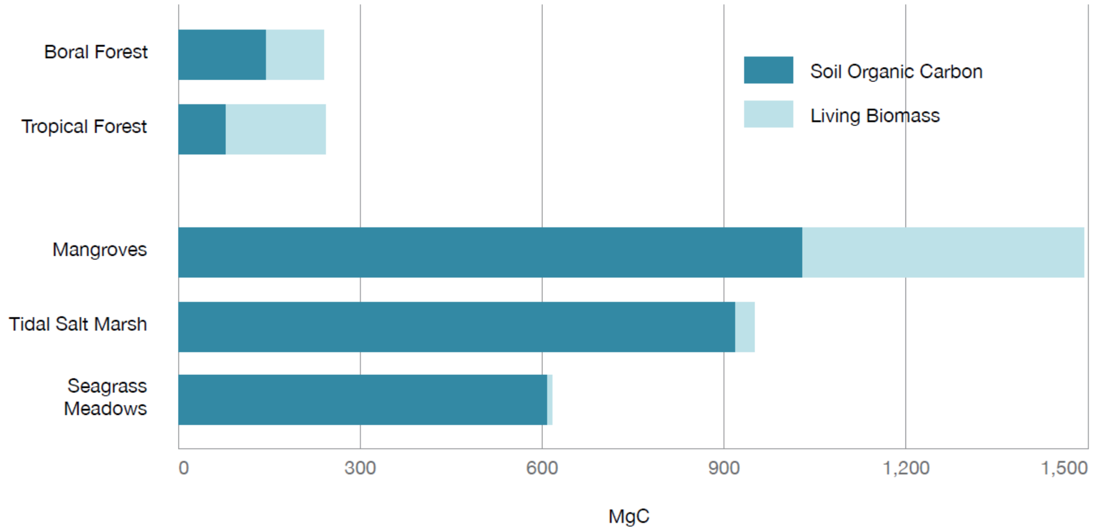


Figure 2-1 A comparison of the mean carbon storage in the above and belowground biomass within terrestrial forests and coastal vegetation ecosystems (Fourqurean et al., 2014b).

The rates of carbon burial, or sequestration, is determined by the rate of accretion and the density of carbon. Despite their smaller coverage coastal vegetation ecosystems have the potential to contribute largely to the amount of carbon sequester. Mangrove and saltmarsh and seagrass vegetation area sequestering more carbon per year than tropical forest, boral forests or temperate forests. So not only are coastal vegetation ecosystems already areas of large carbon stores, they also have the capacity to sequester more carbon than terrestrial forests too.

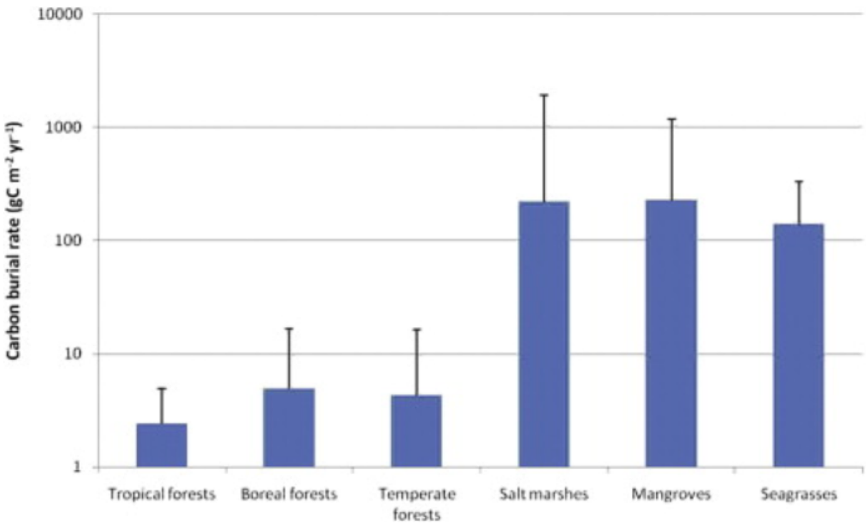


Figure 2-2 Mean long-term rates of carbon sequestration (g C m^{-2} yr^{-1}) within terrestrial forests and vegetated coastal ecosystems. Error bars indicate maximum rates of accumulation (McLeod et al., 2011).

Wetlands are always evolving, but the wetlands we see today started to form after the last interglacial maximum approximately 20 thousand years ago where sea-levels reached 120-140 metres below present. The Holocene Epoch started to occur from 10 thousand years ago and is a period when sea level rose at an average rate of approximately 10 millimetres per year. From 7000 years ago most of the ice that had remained from the last glacial maximum had melted and sea levels around Australia stabilised close to our current levels about 6500 years ago (Short and Woodroffe, 2009). After natural variability, trends around most of Australia show an increased rate of rise in mean sea-level from the early 1990s, consistent with global mean trends (White, Haigh et al., 2014). Recent sea level from 1986 to 2005 indicate a rise in sea level and a continued trend of sea level increase (Figure 2-3). Sea level will likely not be uniform across coastal zones due to different morphology. Approximately 70% of the coastlines around the world are projected to experience sea level change within ±20% of the global mean which is predicted to likely be in the ranges of 0.26 to 0.55 m for model RCP2.6 and between 0.45 to 0.82 cm for model RCP8.5 (Figure 2-3).

.

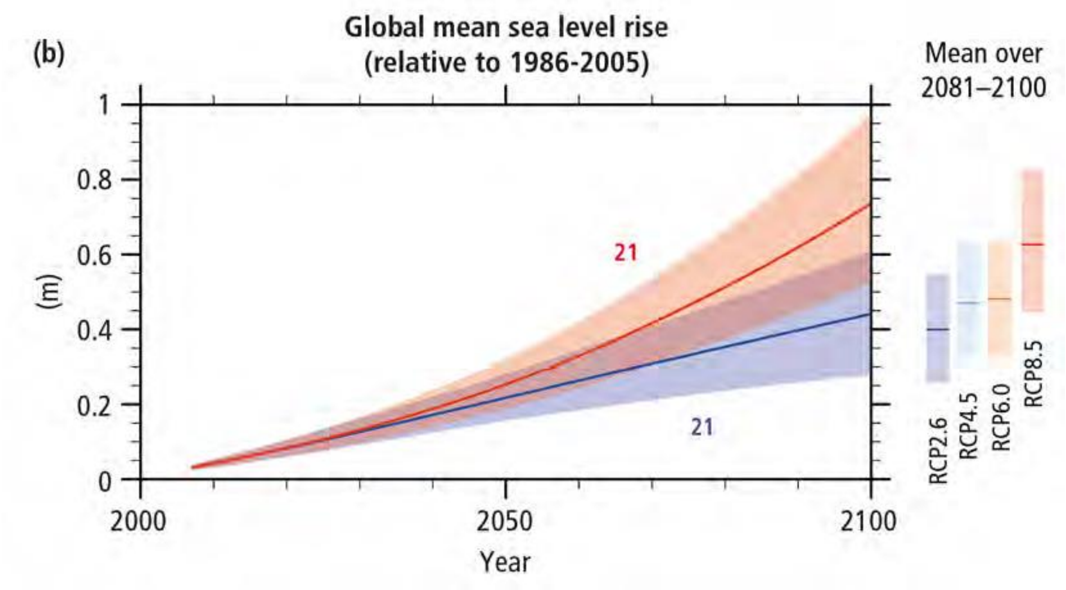


Figure 2-3Global mean sea level rise predicted using values from 1986 to 2005. An obvious trend of increasing sea level is seen (IPCC, 2014).

Wetlands can act as a buffer against inundation from sea-level rise and floodwaters, mostly from the presence of vegetation. They have the capacity to regulate disturbances from storms, floods and drought recovery by the vegetation structure. Coastal zones also provide erosion control and sediment retention services within their soil (Costanza et al., 1998).

Coastal wetlands provide far-reaching ecosystem benefits by contributing to the carbon cycle. An effective carbon sink is one where the rate of carbon entry to a system via photosynthetic pathways or through allochthonous additions is greater than the rate at which it leaves via export or respiration (Breithaupt et al., 2012). Wetland communities with mangroves have sediment surface areas less than 2% of the total marine environment, but they are estimated to store 10 to 15% of the total organic carbon burial in marine environments (Breithaupt et al., 2012).

Wetlands contribute to the carbon cycle through a vegetation and soil medium. In Figure 2-4 below, the carbon cycle showing inputs and outputs in gross tonnage of carbon per year (Gt C yr^{-1}) is depicted for the 1990's (Solomon, 2007). Wetlands play a significant role in this cycle by sequestering carbon.

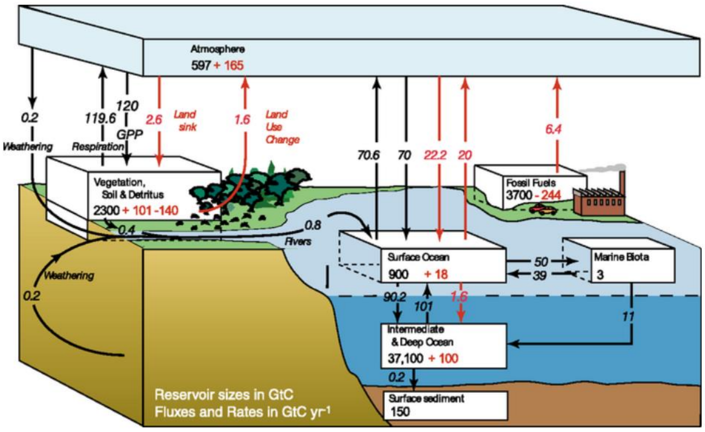


Figure 2-4 the global carbon cycle based on the 1990 decade. Natural fluxes are shown in black and anthropogenic in red. Wetlands specifically shown are not shown, but they are contributors to carbon stores and sequestration through vegetation and soil mediums (Solomon, 2007).

Figure 2-5 depicts the method of carbon sequestration within vegetation both from atmospheric and ocean inputs (Kayranli, 2010). Carbon dioxide is taken up by vegetation and is used in photosynthesis. It indicates the interaction not only with the atmosphere and the plant but with the soil as well, where particulate and dissolved carbon is being stored and carbon is being removed.

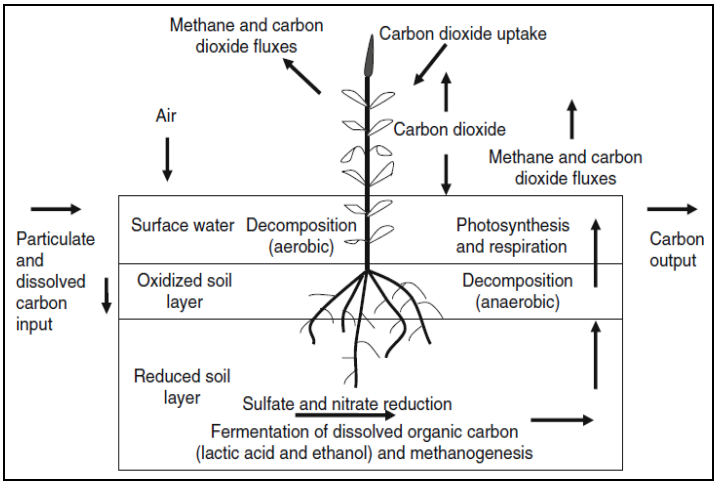


Figure 2-5 Major components of the carbon cycle surrounding vegetation and the pathways including respiration and fermentation causing CO2 to form. In a wetland, organic carbon is converted to CO2 and methane and/or stored in plants, dead plant matter, microorganisms, or peat (Kayranli, 2010).

1.3 Wetland response to sea level rise

Due to current sea-level fluctuations, wetlands are becoming more inundated which could be affecting carbon sequestration and storage. The effect of sea-level rise on sediment accretion and carbon accumulation and its subsequent effect on carbon sequestration and carbon retention remain unknown in many areas of the world (McLeod et al., 2011).

A recent study by DeLaune and White (2012) into the subsiding Mississippi deltaic plain in the USA modelled sediment behaviour due to sea level rise within a saltmarsh (figure 1). They estimated more carbon is being lost in the Mississippi Delta than is being stored or has previously been preserved due to subsidence (Figure 2-6). Carbon stored within wetlands can be lost through a variety of pathways including plant mortality, exportation through erosion and peat collapse.

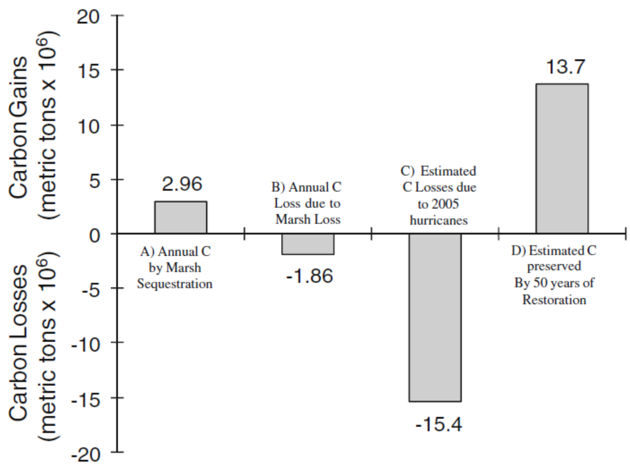


Figure 2-6 Estimated gains and losses of carbon (C) from different coastal processes in the Mississippi Delta (DeLaune and White, 2012).

There method involved creating a model relating to sediment accumulation and then the resultant organic soil loss from subsidence of the deltaic plain. They predict saltmarsh would accrete and eventually not be able to keep up sequestration with water level rise and any organic deposits would be lost within open water or ponding. This model could potentially be related to wetland environments located on the east-coast of Australia, although different tidal velocities, rainfall, wave-energy and biological activity are seen.

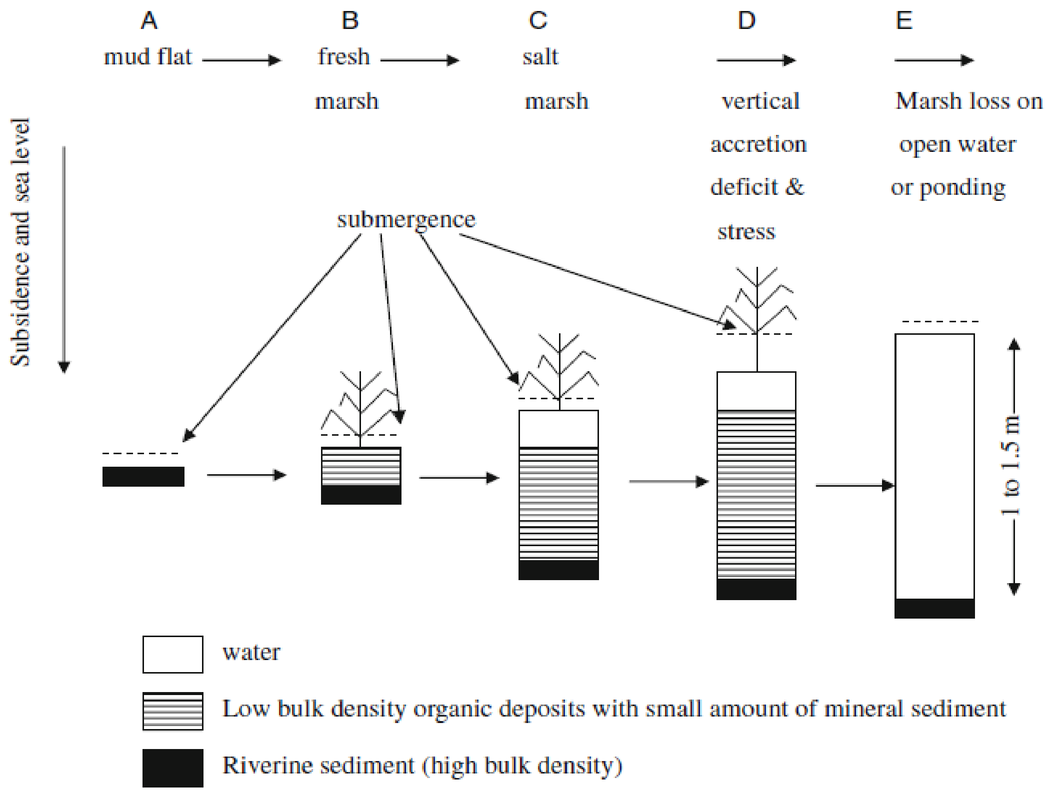


Figure 2-7 Salt marsh organic content accretion and loss due to subsidence, Mississippi Delta, USA (DeLaune and White, 2012).

A study by Mudd et al., (2012) simulated the carbon likely to be lost due to sea level rise within North American marshes dominated by *Spartina alterniflora*. Their simulation suggested climate change will lead to an increase in burial rates in the first half of the twenty-first century but would diminish thereafter and become net carbon emitters. For most of the twenty-first century their model predicts warmer temperatures faster sea level rise and an increase in organic-matter production, carbon accumulation and vertical accretion. By 2100 marshes would be completely submerged and would therefore lose productivity.

With sea level rise it has been estimated that many local changes will occur including altered wave refraction patterns and energy gradients, but estimating changes in wetlands in response to more frequent high tides and storms, seasonal and longer-term changes and on a decadal-century scale remains a challenge (Woodroffe, 2003). Mangrove ecosystems and other wetland communities have a general positive/negative morphodynamic feedback of sediments like the one seen in Figure 2-8 below. Few studies have tried to examine the contribution of organic and inorganic sediments (Masselink and Gehrels, 2014).

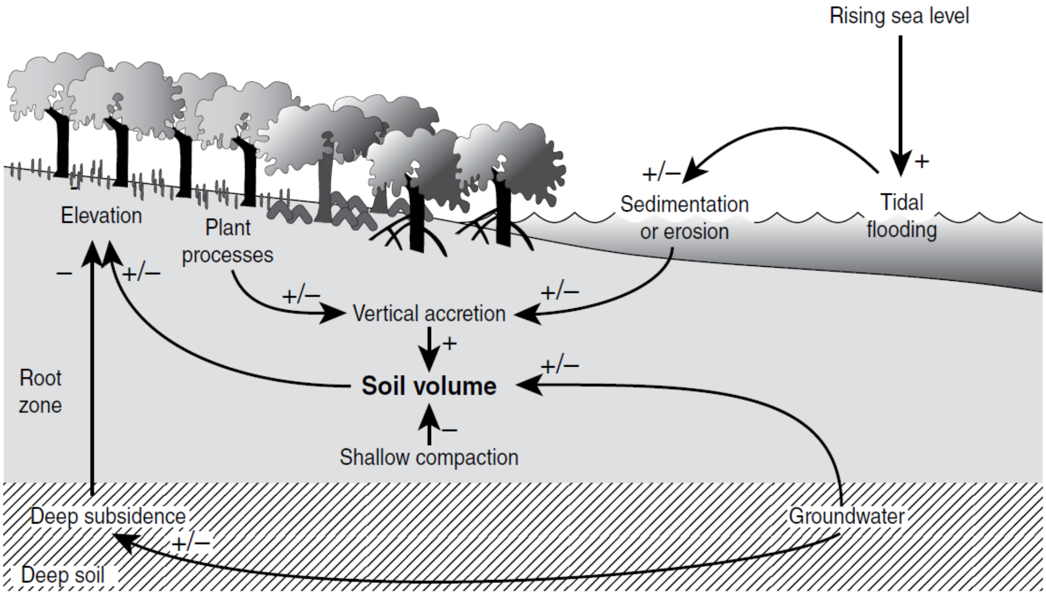


Figure 2-8 Morphodynamic feedback on sedimentation in mangrove ecosystems (Masselink and Gehrels, 2014).

Mangroves and other vegetation can act as an indicator for degrees of inundation and are considered to be in equilibrium with sea level, due to feedback process linked to water depth and accretion (Cahoon et al., 2006). Following moderate sea level rise accretion increases and wetlands may keep pace with water level. If accretion over comes sea level rise the rate of accretion would decline (Woodroffe et al., 2014). Where large increases in sea level occur and sediment supply is reduced, from damming or other structures, it could lead to a loss in wetland area due to an inability of accretion to match sea-level rise (Woodroffe et al., 2014). Carbon sequestration could decline or increase, but the effects of sea level rise on sequestration is not well known (McLeod et al, 2011). Paleoenvironmental reconstruction could provide insight into the response of past mangrove areas to sea level rise and give a clearer understanding to possible future patterns (Woodroffe et al., 2014).

1.4 South-East Australian Wetlands

The south-east coast of Australia is characterised by 42% wave-dominated estuaries, 35% coastal lagoons/strandplain creeks and 10 % wave-dominated deltas and feature large areas of saltmarsh and sparse mangroves (OzCoasts, 2013). Compared to other estuaries around the world, the South-East Australian estuaries are less exposed to relative sea level rise, hurricane impacts and enhanced wave energy like those located in the Gulf of Mexico where previous carbon sequestration and storage studies have been conducted (DeLaune and White 2012).

Chain Valley Bay at Lake Macquarie, NSW was selected as a study site and is located with the South-East Australian coastal zone. According to Roy et al., (2001) the Lake Macquarie estuary are wave dominated, barrier estuaries. In addition, Lake Macquarie is at a youthful evolutionary stage (Roy et al., 2001). The estuarine characteristics seen at Lake Macquarie are also seen at 6 other estuaries on the south-east coast of Australia and together they have an average area of 1.16 (0.04) km^2 mangrove and salt marsh vegetation per estuary and an average area of 8.85 (0.30) km^2 seagrass vegetation per estuary (Roy et al., 2001).

Chain Valley Bay was chosen as a study site due to the recent mining subsidence from 1986 that caused inundation of the wetland located within the Bay area. The rapid inundation provides the opportunity to use it as a surrogate for rapid sea-level rise. A schematic diagram of the mining subsidence that occurred from the partial pillar extraction within the long wall mine under the wetland is shown in Figure 2-9. Clay quickly shears causing load to fall onto the rock bands that eventually fail causing the roof to collapse (Mcnally, 2014).

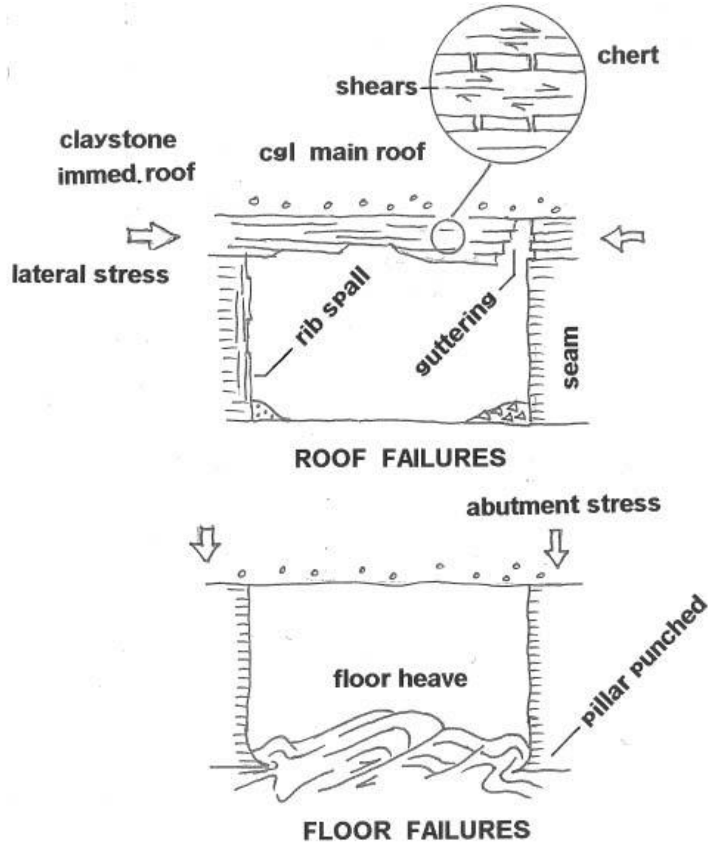


Figure 2-9 Claystone roof and floor failure likely seen at Chain Valley Bay causing subsidence of the Wetland (Mcnally, 2014).

1.5 Carbon Accretion

The coastal zone is a constantly evolving medium but its evolution is recorded within its sediments as stratigraphic layers, i.e. clay, silt, sand and gravel (Masselink and Gehrels, 2014). More importantly sediment records show discontinuities which could indicate an erosional event. By dating the stratigraphic layers within sediments in wetlands and other coastal deposits, the rate of accretion can be quantified and help in the reconstruction of sea-level history (Masselink and Gehrels, 2014).

Coupled with stable carbon isotope anaylsis, sources of carbon within organic material can be determined and a quantification of carbon sequestration capability of the wetland following submergence can be calculated.

The lead-210 technique is used to calculate sedimentation rates by the determination of polonium-210 (^{210}Po) and radium-226 (^{226}Ra) activities within sediment cores. Changes in mass accumulation and accretion can be determined using this technique. Lead-210 was chosen as an aging technique for the Chain Valley Bay sediments because of its relatively short half-life ($t_{1/2}$=22.23 years) which is useful for applied environmental investigations (Dalrymple, 1992). Isotope ^{137}Cs was not used because its half-life was too short. ^{210}Pb is a naturally occurring radioisotope and is a product of the ^{238}U decay series below.

$$^{238}U \rightarrow {}^{226}Ra \rightarrow {}^{222}Rn \rightarrow {}^{218}Po \rightarrow {}^{214}Bi \rightarrow {}^{214}Po \rightarrow {}^{210}Pb$$

^{226}Ra and ^{210}Pb are not in secular equilibrium within natural materials due to the diffusion of ^{222}Rn into the atmosphere and soil. A fraction of ^{222}Rn diffuses from geological and soil material into the atmosphere or upper soil layers, causing disequilibrium between ^{226}Ra and ^{226}Rn. During the atmospheric release of ^{226}Rn daughter products are attached to the surfaces of aerosols and dust particles, including the ^{210}Pb daughter isotope (Dalrymple 1992). The daughter isotope reaches the ground by washout from the atmosphere, within eroded material and in-wash from catchments and accumulates within the surface layer (Figure 2-10). The ^{210}Pb within the surface layer is supported ^{210}Pb and is in equilibrium with ^{226}Ra and will decrease with the half-life of ^{226}Ra which is approximately 1600 years. Unsupported ^{210}Pb is excess and decays by the physical half-life of ^{210}Pb. The unsupported or excess ^{210}Pb is the basis of most tracer applications.

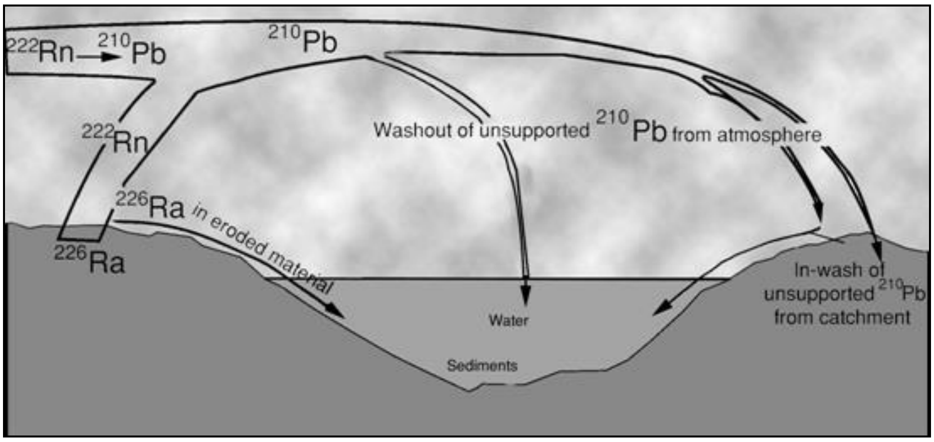


Figure 2-10 A schematic diagram of the movement of supported and unsupported daughter isotope ^{210}Pb into the sediments from the atmosphere, erosional material and in-wash (Oldfield and Appleby, 1984).

1.6 **Capacity to store and sequester carbon**

A useful characteristic of terrestrial vegetation is it can be separated according to photosynthetic pathways, these being C_3, C_4 and Crassulacean acid metabolism (CAM) plants (O'Leary, 1988). For C_3 plants the Calvin cycle is used where plants fix CO_2 by the action of the enzyme ribulose biophotosynthetic carboxylase and for C_4 plants the Hatch-Slack cycle is used where CO_2 is initially taken up through carboxylation of phosphoenolpyruvate (O'Leary, 1988). Plants are able to differentiate between ^{12}C and ^{13}C isotopes which can be revealed through carbon isotope analysis where a $\delta\ ^{13}C$ value is obtained using the formula below:

$$\delta^{13}C = \left[\frac{R(\text{sample})}{R(\text{standard})} - 1\right] \times 1000$$

A more negative $\delta\ ^{13}C$ value means more ^{12}C or lighter in mass and a more positive value means ^{13}C or heavier in mass (figure 1).

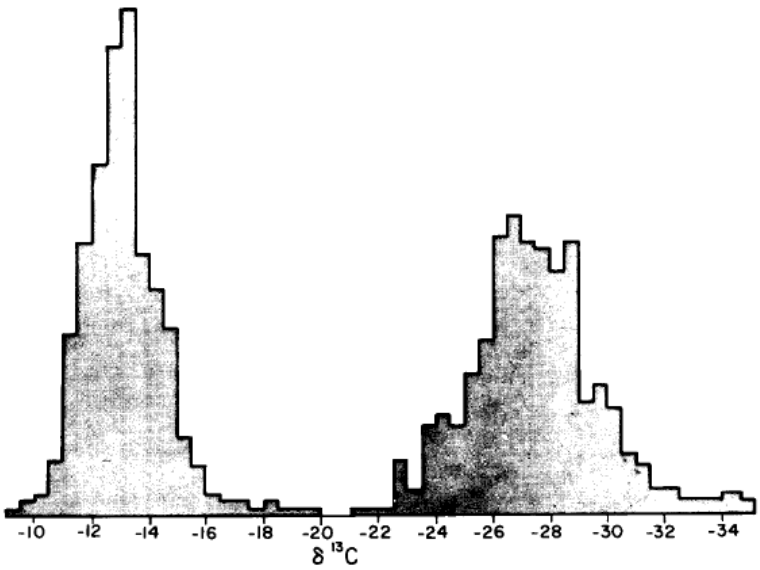


Figure 2-11 The distribution of $\delta\ ^{13}C$ values of plant material where values approximately -14‰ are C_3 plants and values approximately -28‰ are C_4 plants (O'Leary 1988).

Small differences in chemical and physical properties of plants allows then to discriminate against ^{13}C and be assigned a photosynthetic pathway (O'Leary, 1988). This differentiation between vegetation is useful in identifying the carbon sources within sediments and gives us the opportunity to create a history of accumulation within sediments like those found in wetlands (Choi et al., 2001).

The amount of carbon within the core can be identified using isotopic techniques and bulk density. This value coupled with accretion provides a rate of sequestration.

3. REGIONAL SETTING

1.7 Study site location

The Lake Macquarie tidal estuary is located on the central coast of New South Wales, Australia (33°5’36.145’’S 151°35’20.335’’E) (Figure 3-1). The lake is highly valued by nearby residents and visitors to the area and is used for recreation activities such as fishing, sailing and swimming. The focus area of this study is the Chain Valley Bay wetland located within the Lake Macquarie estuary at its most southern point (33° 10'S, 151° 34'E). Chain Valley Bay is within the Wyong Local Government Authority (LGA). The urban area of Chain Valley Bay adjacent to the wetland is relatively small, covering about 6 km^2 with an approximate population of 2,500 people (Australian Bureau of Statistics, 2013).

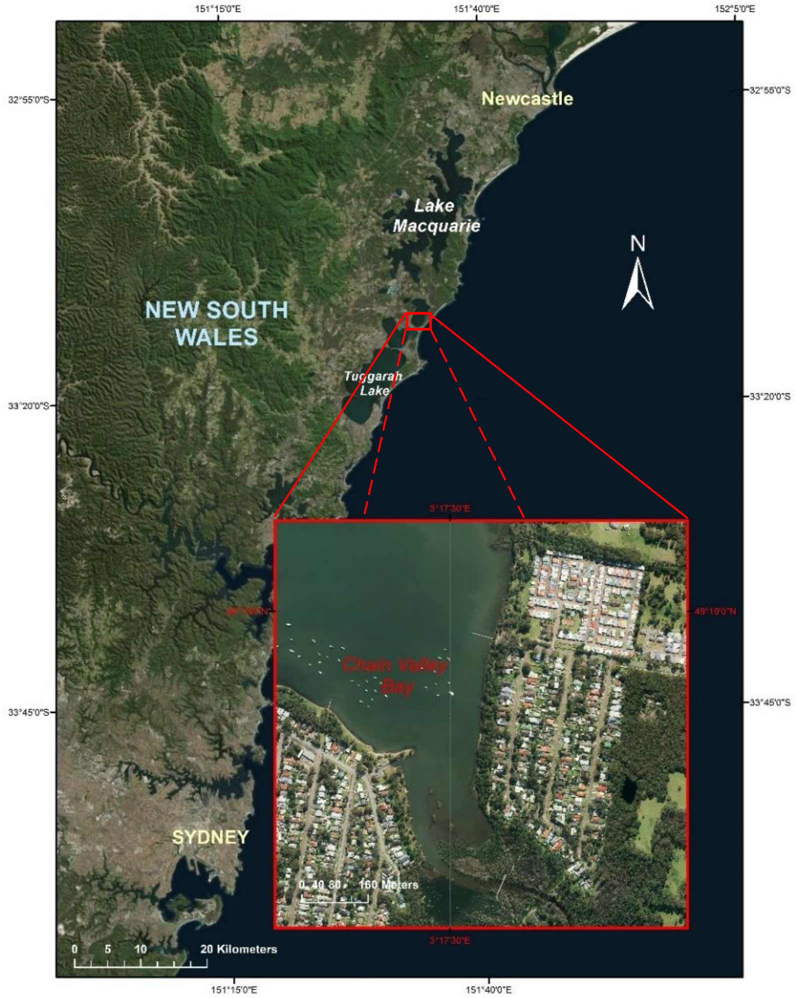


Figure 3-1 The study location Chain Valley Bay in its wider context on the New South Wales central coast and the wetland in 2014 (Basemap source: Esri, DigitalGlobe, GEOEye, i-cubed, Earthstar, Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community. 2014 aerial map source: Wyong Shire Council).

1.8 **Industrial activity at Lake Macquarie**

Lake Macquarie is part of the Sydney Basin and is within the Newcastle coal formation (Figure 3-2). Industrial development and mining at Lake Macquarie has allowed the region to expand in population and wealth, and has a history of coal mining since the late 1800's. Large coal firms such as Centennial Coal which is the largest underground coal producer in NSW, are currently mining within the Lake Macquarie area today and utilise the Newcastle port approximately 15 km to the North of Lake Macquarie to export. Current mining activity at Chain Valley Bay is being undertaken by LakeCoal at the Chain Valley colliery which is near the wetland study site (refer to Figure 3-4). The Chain Valley Colliery became operational in 1962 and has conducted coal extraction within the Wallarah, Great Northern and Fassifern coal seams (Figure 3-3) (LakeCoal, 2012).

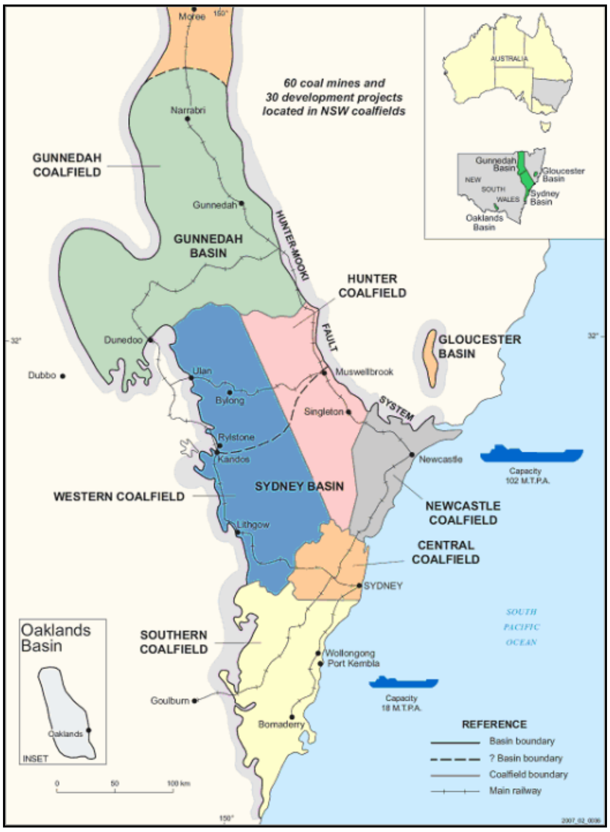


Figure 3-2 Coalfields within the Sydney Basin, NSW. Lake Macquarie is located in the Newcastle Coalfield (NSW Dept TIRE).

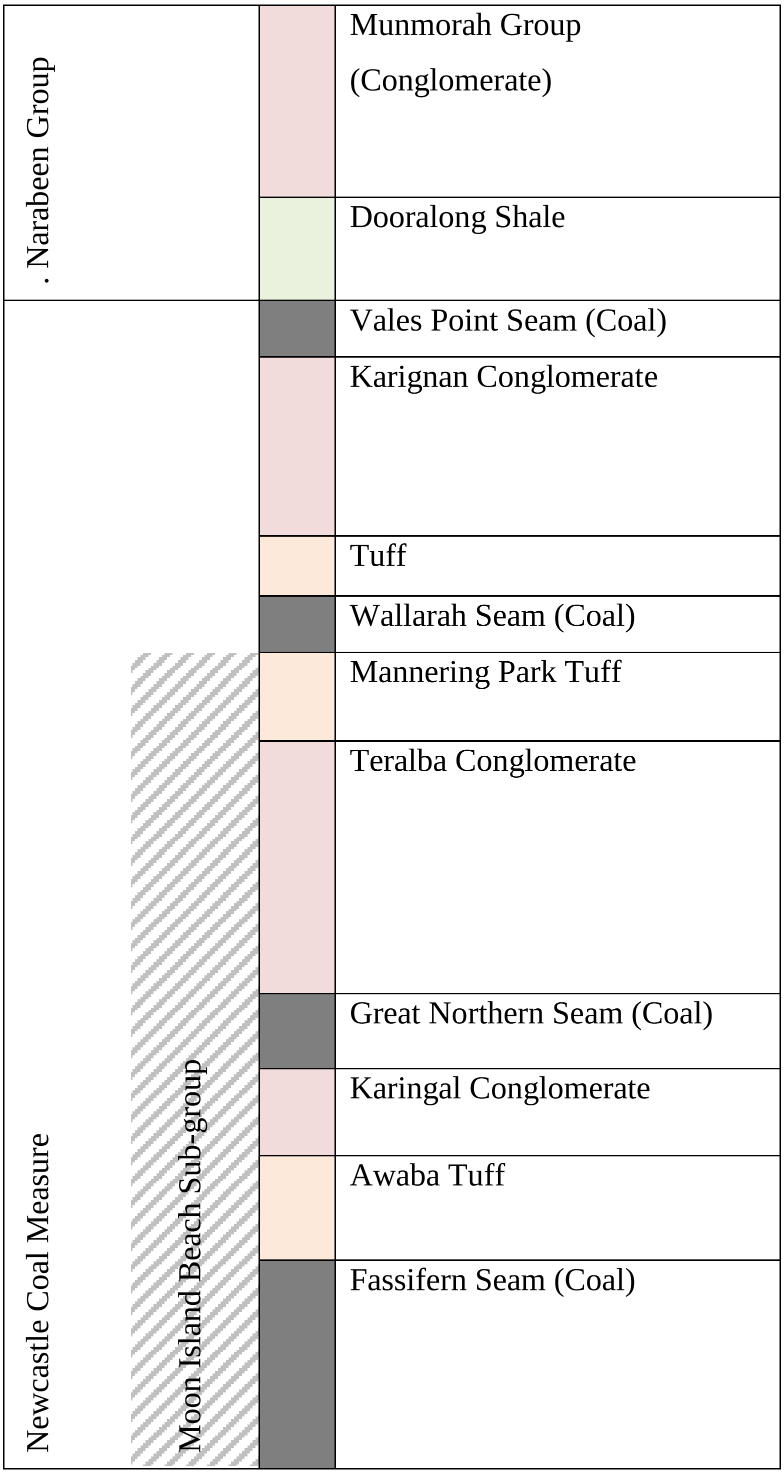


Figure 3-3 Local stratigraphy at Chain Valley Bay Colliery (diagram based on one by LakeCoal, 2013). Wallarah, Great Northern and Fassifern coal seams have been mined at the Chain Valley Colliery.

Lake Macquarie also has power stations located around the lake with Eraring Power Station located on the Western Shore of Lake Macquarie approximately 30 km south-west of Newcastle, Colongra Power Station located approximately 4 km south-west from the study site and the Vales Point Power Station located approximately 3 km north- east from the study site (refer to Figure 3-4). The Vales Point Power Station draws water for condensate cooling from Chain Valley Bay (Delta Electricitym 2014).

Elcom Collieries Pty Limited was operating under Chain Valley Bay including the area under the wetland and allegedly mining from the Newvale Colliery illegally (Aecomm 2011). In 1986 the Chain Valley Bay wetland and its surrounds started to encounter lateral and vertical subsidence due to a collapse in the underground long wall mine operating underneath (MSB, 2007). Rapid inundation occurred as elevation reduced and the wetland encountered environmental change. Low lying areas of the foreshore including private residences became prone to flooding and inundation. Initial measurements of the subsidence in 1986 were approximately 500 mm and grew to 607 mm in June of 1987. Subsidence continued and by June 1988 the subsidence had increased to 750 mm and by December 1988 subsidence was recorded at 782 mm (MSB, 1991). The remediation works at the site due to subsidence included (MSB, 1991):

- Raising of 11 houses, and an additional 38 homes required varying degrees of repair or restoration.
- The filling of 27 privately owned lots.
- The filling of approximately 3 km of Karignan creek and Lake Macquarie frontage areas.
- Restoration of an existing car park and boat ramp.
- The relocation and modification of services (telephone, electricity, water and sewer lines).
- Landscaping/tree planting programme.

By 1989 subsidence had reached 818 mm and in 1991 850 mm of subsidence had occurred (MSB, 1991). During a visit to the Chain Valley Bay site in 2014 a nearby resident (2014 pers. comm., 8th September) verified subsidence was still occurring.

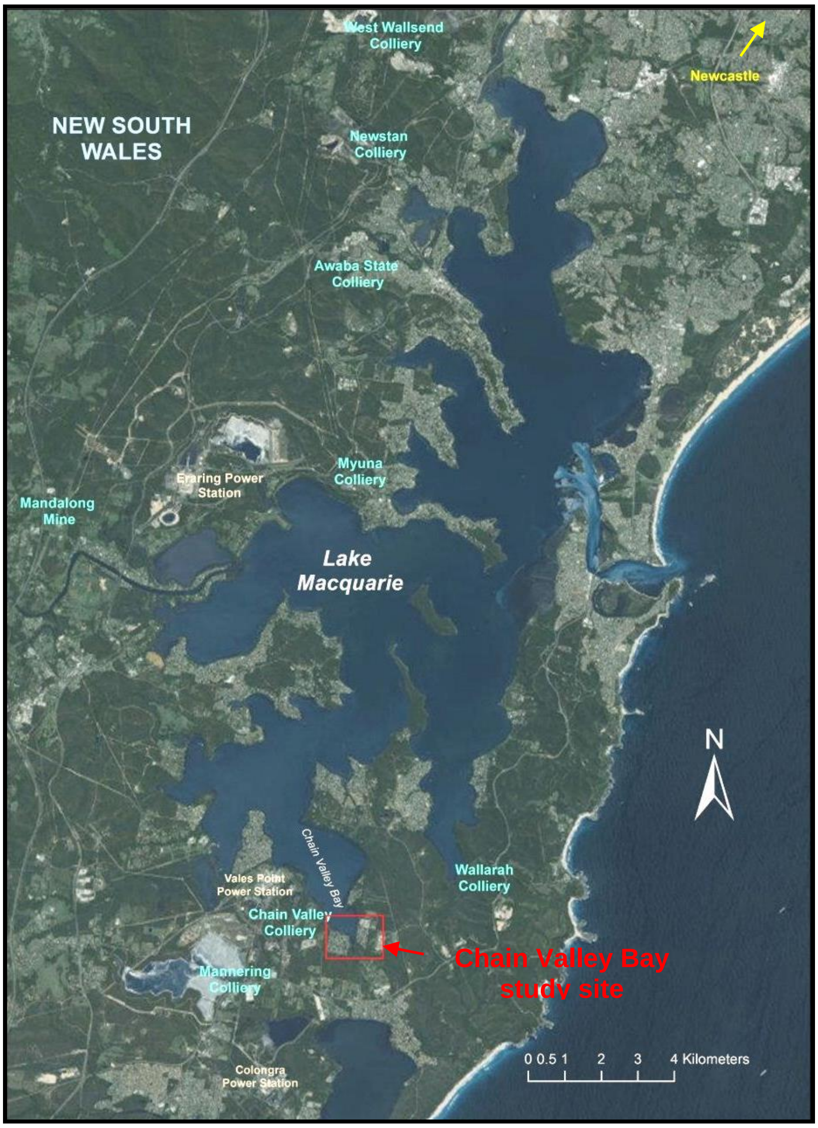


Figure 3-4 Approximate locations of collieries, mines and power stations surrounding the study site and Lake Macquarie (Base map source: Esri, DigitalGlobe, GEOEye, i-cubed, Earthstar, Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community. 2014 aerial map source: Wyong Shire Council).

1.9 Coastal geomorphology and estuarine dynamics

Estuaries are dynamic coastal environments that experience change from short term climatic conditions and long term geological change. Longer term geological change is evident when we see a natural progression of large estuarine water bodies to terrestrial flood plains, levees and back swamps. The ecology of estuaries is often affected by this geomorphic progression.

Lake Macquarie and other South-East Australian estuaries can be classified based on a particular set of characteristics (Roy et al., 2001). Two main types of estuaries, tide-dominated and wave-dominated, are classified by geological criteria and entrance conditions controlling tidal exchange. These factors control sediment infill amounts and the depositional environment within estuaries and play a further role in the substratum conditions, hydrological regimes and nutrient cycling behaviour demonstrated through biological activity. Lake Macquarie is classified as a wave dominated, youthful barrier estuary because it is a large body of water within the early stages of infill and with a barrier at its entrance (Roy et al., 2001). Barrier estuaries are separated from the open ocean by a sand barrier which has occurred due to landward reworking of sand from the shelf (Woodroffe, 2003). These types of estuaries support a diverse range of estuarine habitats including marine and brackish, sub-tidal, intertidal and supra-tidal (Ryan et al., 2003). Lake Macquarie has low river flow with only several creeks draining into the central mud basin and low turbidity unless a high wind or rainfall event occurs. The central basin of Lake Macquarie is a trap for sediments and pollutants and encourages denitrification of terrigenous nutrient load (Ryan et al., 2003).

Lake Macquarie has tidal inlets that are constricted by beach sand deposited by wave action and flood-tidal deltas. The tidal range within this type of estuary is usually significantly less than ocean tides and the tidal currents are usually weak, due to significant attenuation of tidal amplitudes as tides enter the expansive water body (Figure 3-5). The dominant sediment transport mechanisms are wind and water movement from wind action. The youthful stage of the lake means it is still experiencing infilling and it has been predicted when infilled Lake Macquarie would be a riverine estuary (Roy et al., 2001), much like the Shoalhaven River located approximately 200 km south. The transformation from a barrier estuary to a riverine estuary is due to the depositional environment of Lake Macquarie and is represented through changes in water surface area characteristics as shown in Figure 3-6. Marine flood-tidal delta, central mud basin, fluvial delta and riverine channel/alluvial plain are areas common to each type of estuary and correspond to readily mapped sedimentary environments in estuaries of South-East Australia. These zones can be modified or separated based on estuary type, stage of sediment filling/maturity and development impacts.

The basic characteristics of the Lake Macquarie catchment area as of 2013 include an estuary area of 114.1 km^2, a catchment area of 604.4 km^2, an average water depth of 5.7 metres and an estuary volume of 646 274 ML (OEH, 2013).

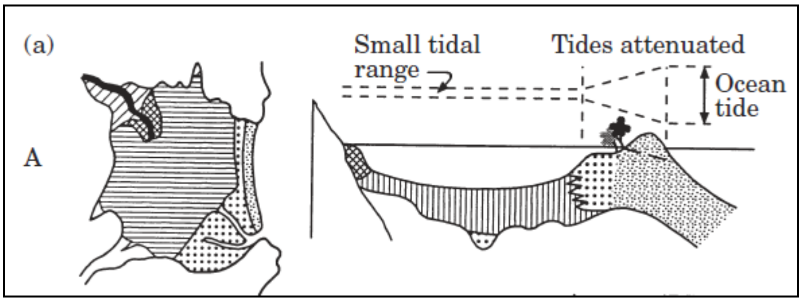


Figure 3-5 Stage A or youthful stage of infilling in a barrier estuary like Lake Macquarie (Roy et al., 2001). The tidal range is smaller than evolutionary stages B, C and D.

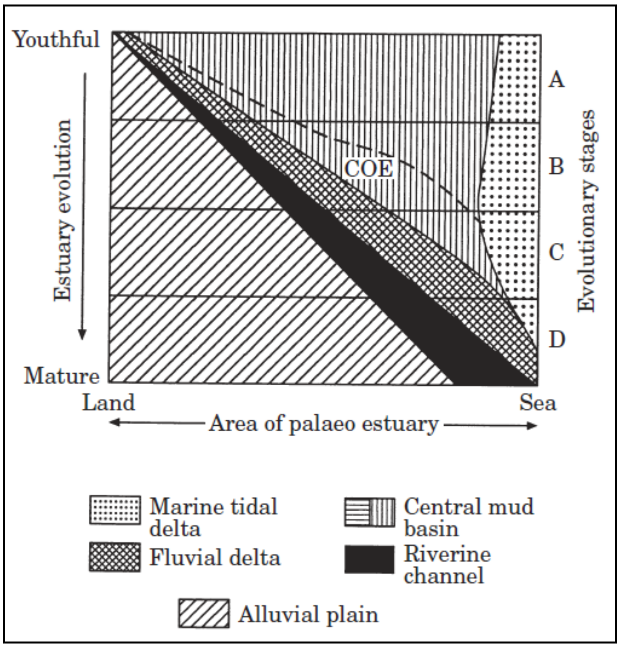


Figure 3-6 Changes in surface area of different depositional environments in the transition of an estuary from youthful to mature (Roy et al., 2001). *Note: COE = Cut-off embayment's.*

1.10 **Climate**

The Lake Macquarie estuary exists in a temperate climate (OzCoasts, 1998). Like most of South-East Australia, Lake Macquarie has a decrease in air temperature from May to August and has an increase in temperatures over the summer months of November to February. The closest weather station to Chain Valley Bay with a record of temperature is Cooranbong

(Lake Macquarie AWS), station number 61412, located 17.9 km away to the north-west and opened in 2008. In 2014 the station recorded a mean maximum temperature of 23.9 °C and an annual mean minimum temperature of 11.6 °C (BOM, 2014a) . A weather station at Swansea (Catherine St), station number 61377, is located 4.4 km from Chain Valley Bay and has a record of rainfall from 1993. At this site in 2014 the highest mean rainfall was observed from Febraury to June and there was a total of 1252 mm of rainfall recorded for the entire year (BOM, 2014b).

1.11 **Tides**

Hydrological activity within Lake Macquarie plays a major role in sediment transport. Major focus has been placed on sedimentation, erosion, and the stability of the Lake Macquarie entrance. Changing entrance conditions gives rise to issues relating to navigation, foreshore stability, tidal exchange and ecological sustainability (Witt et al., 1996). Any changes to the entrance channel can affect ecological conditions. For example, seagrass beds are located within the lake and are dependent on the lake water levels. If there are changes to entrance conditions resulting in larger tidal movement or water inundation the seagrass beds will be affected by the active sediment movement and could be blanketed by sediments causing suffocation (Witt et al., 1996).

It is suggest by Roy et al., (2001) the distribution of mangrove and saltmarsh vegetation is controlled by the tidal range. Lake Macquaire is a barrier estuary and the fluvual delta zone is less extensive with more restricted areas of mangroves and saltmarshs. When compared with the evolution of estuaries, mangrove and saltmarsh are less abundant in barrier estuaries. There is also a trend of expanding saltmarsh and mangrove area with increasing maturity (Roy et al., 2001).

Tidal information for water bodies like Lake Macquarie can indicate the tidal prism of the estuary and circulation (Woodroffe, 2003). The tidal prism is the volume of water moving past a cross section with tidal movement. Tidal prisms are classified based on circulation and can either be salt-wedge, partially mixed or well-mixed. Tidal information has been recorded approximately 500 m upstream of the entrance to Lake Macquarie in 1996 (OEH, 2013). A local tidal range of 1.18 m was recorded at ebb flow and at flood flow a local tidal range of 1.16 m was recorded. In comparison Sydney Harbour which is also included within the South-East Australia estuary group and located approximatly 90 km south of Lake Macquarie has higher ebb flows of 1.34 m and higher flood flows of 1.29 m. This is due to the harbour being a tide dominated drowned valley estuary, thefore having larger tidal ranges than Lake Macquaire which is mostly sheltered from tidal influence (OEH, 2013). Both sites located on the south-east coast have low spring tidal ranges. Most coastal zones in South-East Australia have high tides approxiamtly around 1.5 m and low tides around 0.3 m (BOM, 2015).

At Lake Macquarie the tidal prism would likely be a combination of salt wedge and partially mixed circulation due to the low tidal exchange (Woodroffe, 2003). Figure 3-5 above gives an indication of the small tide and the attenuating tidal power likely in Lake Macquaire. Lake Macquarie also has a semi-diurnal cycle where two high and two low tides of approximate equal size are experienced every lunar day.

It is likley the tidal range within Lake Macquaire will increase with sea level rise. Using two sites within Lake Macquaire, these being Belmont approximatly 17.5 km north-east and Marmong Point approximatly 22 km north of the Chain Valley Bay wetland, Watterson et al., (2009) have predicted the possible effect sea level rise. Assuming a static ocean tidal range, the lake spring tidal range will likely steadly increase at a rate of 0.0012 per/yr at Belmont and 0.0011 per/yr at Marmong point (Watterson et al., 2009).

1.12 Winds and waves

The South-East Australian coast is dominated by southerly swells which help in the movement of sediments through littoral cells and within tidal inlets and deltas. From wind data collected at 3pm from 1969 to 2004 at Norah Head Lighthouse, site number 061273 located approximately 11.5 km south-east of Chain Valley Bay, the dominant wind direction is south and north-east. Southerlies are seen from March to September in the cooler months and a north easterly is seen from October to February. Wind is stronger at 3pm than those at 9am, and is predominantly ≥ 20 and <30 km/h. The average annual wind speed at 3pm is 20.8 km/h and 14.4 km/h at 9am (BOM, 2014). Assuming wind direction and speed recorded in this location corresponds to Lake Macquarie, waves within Lake Macquarie would likely travel in a north and south-westerly direction, depending on the season. During site visits in late August and January to the Chain Valley Bay wetland wave direction was seen to be travelling in a south-westerly direction around the small headland/boat ramp towards the eastern section of the Chain Valley Bay wetland.

Even though Lake Macquarie is characterised as a wave dominated estuary by Roy et al., (2001) the impact of wave energy on sediment movement within the lake is limited. According to Adlam's, (2014) theory on geologic evolution of lagoons like Lake Macquarie that remain unfilled despite thousands of years of sedimentation, they are unfilled due to the lagoons not reaching a threshold at which orbital motions of wind waves are able to suspend sediments within the central mud basin. Other lagoons following infilling until the basin is sufficiently shallow, have wind orbital motions preventing deposition or entrainment of sediments as a results of a threshold shear strength being exceeded. Lake Macquarie is limited by sediment supply and has wave orbital motions that do not interact with the central mud basin (Figure 3-7).

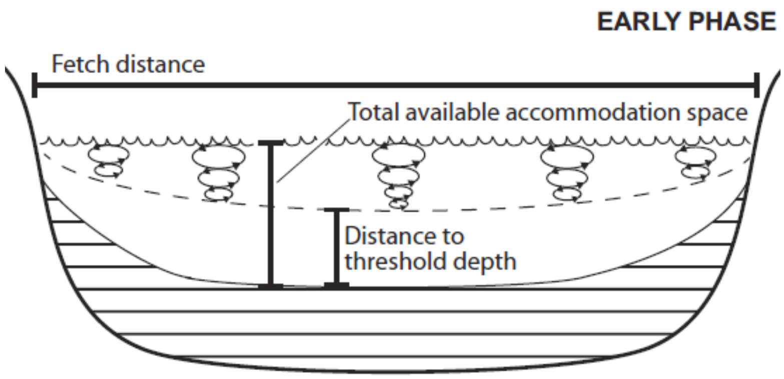


Figure 3-7 The Wave orbital motions within Lake Macquarie that is currently unfilled. The lake is deeper than the threshold depth due to low sediment supply (Adlam, 2014).

1.13 **Ecology**

Lake Macquarie has characteristic barrier estuary vegetation with mangrove, salt marsh and seagrass coverage. The approximate area of mangrove within the lake is 1.00 km^2 with patchy cover, and extensive seagrass with approximate area of 13.39 km^2 which is consistent with the distribution of estuarine vegetation within relatively immature barrier estuary. Salt marsh area only covers approximately 0.71 km^2 and is patchy (OzCoasts GeoScience Australia, 2012). Sediment infilling of the youthful estuary will likely cause a transition from conditions with a lot of subaqueous area suitable for seagrass vegetation to the development of extensive intertidal surfaces suitable for mangrove and saltmarsh development and growth. The only mangrove species occurring at Lake Macquarie are *Avicennia marina* (Grey mangrove) and *Aegiceras coniculatum* (River mangrove) species. *Avicennia* is the dominant species found at the Chain Valley Bay wetland.

The vegetation at Chain Valley Bay is not only mangrove but Coastal Saltmarsh which adjoins mangrove at Chain Valley Bay. It occurs as groundcover in the upper intertidal zone on the landward side of the mangrove area at Chain Valley Bay. Common species include to Lake Macquarie include *Juncus krausii* subsp. *Australiensis* (Sea Rush), *Sarcocornia quinueflora* subsp. *quinqueflora* (Samphire) and *Sporobolus virginicus* (Marine Couch), *Baumea juncea* (Bare Twigrush), *Ficinea nodosa* (Club Rush), *Selliera radicans* (Swampweed), and in brackish areas tall reeds such as *Phragmites australis* (LRO, 2009). Mangrove occurs scattered through some of the saltmarsh area at Chain Valley Bay.

The saltmarsh area transitions to Swamp Oak Floodplain Forest which is characterised by *Casuaina glauca* (Swamp Oak) and/or *Melaleuca quinquenervia* (Broad-leaved Paperbark). (LRO 2009).

Seagrass species common to Lake Macquarie include *Zostera capricorni* (Eel Grass) *Posidonia australis* (Strap Weed), *Halophila ovalis* (Paddle Weed) and *Ruppia megacarpa* (Sea Tassels) (AWACS et al., 1995). The seagrass species *Zostera capricorni* was present at Chain Valley bay in extensive seagrass wrack located on the shore of the wetland.

1.14 **Chapter Summary**

Lake Macquarie is located on the central coast of NSW and has mixed land use with significant areas of natural vegetation, urbanisation and infrastructure. The study site is located at the southernmost point of the lake at Chain Valley Bay. Lake Macquarie is an area with high proportion of collieries and power stations due to the abundance of coal seams within the Newcastle coalfield. The local region has moderate summers and winters and rainfall. The lake is a wave-dominated barrier estuary and because of this has low tidal ebb and flow tides. The local wind speed is general >=20 and 30 km/h and are predominantly southerlies and north-easterlies and change with the seasons. Wave direction follows the direction of wind movement in the lake and waves are generally small and produced by the wind. Waves travel towards the entrance to the Chain Valley wetland and encounter the front of the wetland on the eastern shore. Predominate marine vegetation in the lake are sea grass species extending 13.39 km^2 and terrestrial species of mangrove extending 1.00 km^2.

4. METHODOLOGY

The intent of this study is to measure carbon and analyse blue carbon systems at a regional scale at Chain Valley Bay, Lake Macquarie after a major inundation event due to mine subsidence. The subsidence that has occurred from 1986 is a surrogate for rapid sea-level rise. This was achieved by undertaking spatial analysis using remote sensing techniques, using ^{210}Pb radiometric dating techniques on sediments to determine rates of accretion and mass accumulation and using carbon isotopic methods to determine carbon sources and the percentage of carbon within the wetland with depth. These methods are discussed below.

1.15 **Spatial Analysis**

Remote sensing is a useful tool to study distribution where no previous sampling and analysis have been undertaken and where a level of spatial detail cannot be captured readily with ground-based techniques. Using spatial analysis techniques, information on wetland vegetation structure and coverage can be mapped where they previously could not.

Remote sensing is an effective medium to estimate ecosystem extent, plot design and biomass measurements. It has previously been used to analyse coastal land use and potential carbon sink change over time and could potentially be used for national carbon accounting (DeLaune and White 2012; Fourqurean et al., 2014). The ESRI Geographic Information System mapping program ArcGIS was used for spatial analysis in this study.

1.15.1 Vegetation Change mapping

Vegetation distribution at various time intervals can provide an effective representation of wetland change over a short period of time due to external changes within the environment. At Chain Valley Bay the distribution of vegetation has been effected by inundation and vegetation is used as a representation of inundation zones. Mangrove and saltmarsh roughly occupy the zone between mean sea level and highest astronomical tide.

Mapping of vegetation change over time within the wetland at Chain Valley Bay was undertaken using ESRI ArcGIS version 10.2. Subsidence of the wetland caused rapid inundation from 1986 to 2014 (pers comm. Chain Valley Bay resident). The time period from 1984 to 2014 was used to map changes in vegetation due to the event. Historical aerial photography of the wetland were assigned projected coordinate system GDA-1994-MGA-Zone 56 and geographic coordinate system GSC-GDA-1994. Using the Georeferencing tool on ArcGIS the imagery were aligned and adjusted using at least 12 control points and a RMS error below 1.5 was ensured. Independent ground control points similar to each photo like edges of buildings, driveways, pools and tennis courts, were used as references in each aerial photograph. Locations around Chain Valley Bay where change is likely to occur, for example in the wetland, were not used as references. Photography was georeferenced in order from 2014 to 1984. The 1996, 2003, 2006 and 2010 aerial photography was georeferenced to 2014 which was received from Wyong Shire Council already georeferenced. Historical photography from 1984, 1986, 1987 and 1990 were georeferenced using 1996 photography because common control points could not be found for these images in more recent photography.

The historical aerial photography was then digitised to show vegetation change over time following the subsidence event, using a maximum scale of 1:1500. Four categories were assigned including a zone of impact and basic vegetation classes Mangrove, Saltmarsh and Mixed Forest. The classification of each zone is shown below:

- Zone of Impact: Where vegetation is predominantly dead or dying including dead saltmarsh, mangrove, casuarina and swamp paperbark.
- Mangrove: Mangrove forested areas where species like *Avicennis marina* (Grey mangrove) are dominant and an approximate density of 90% mangrove trees are present.
- Saltmarsh: Open spaces and pools where species common to the saltmarsh like *Juncus krausii subsp. Australiensis* (Sea Rush) and *Sarcocornia quinueflora subsp. Quinqueflora* (Samphire) are dominant and cover approximately 90% of area.
- Mixed Forest: Where *Casuarina glauca* (Swamp Oak) is the dominant vegetation species and is interspersed with *Melaleuca quinquenervia* (Broad Leafed Paperbark). This zone would include associated vegetation cover of approximately 90%.

Each zone was delineated in accordance with the protocols of Wilton and Saintilan, (2000) which recommend a scale of 1:5000 or larger for differentiation of mangrove and saltmarsh and georectification using at least 6 ground control points.

There is some *Casuarina glauca* vegetation spread randomly throughout the saltmarsh area and some sections of mangrove have saltmarsh patches. It should be noted vegetation zonation using aerial photography can create associated errors which cannot be avoided. Mapped zonations are only an indicator of vegetation zones at the time the photo was taken.

Change in the extent of each vegetation class between available years was calculated by image subtraction and tabulated based on percentage of change per year. A graph representing total change (m^2) through time within each vegetation class was created.

1.15.2 Ground Truthing

Site reconnaissance conducted in September and December 2014 and earlier ground truthing advice provided by Kerrylee Rogers from visits in May and June 2014 allowed for the corroboration of the aerial photography vegetation classification and zonation. The existing environment was recorded using digital photography and common vegetation types in each zone were observed. During this exercise it was noted that some *Melaleuca quinquenervis* occurred in the areas thought to be *Casuarina glauca* alone. As a consequence *Casuarina* and *Melaleuca* areas were combined in the spatial mapping as mixed forest. During site inspections some *Casuarina glauca* species were observed intermittently through saltmarsh areas.

1.16 **Wetland Morphology**

1.16.1 Digital Elevation Model

Ground topography is used to show areas likely to be inundated by tidal forces, high flood events or even sea-level rise. It can also indicate sediment infill areas and areas likely to be in-filled in the future. A digital elevation model (DEM) was created in ESRI ArcGIS using Light Detection and Ranging (LIDAR) data obtained from NSW Land and Property Information (LPI) allowing analysis of the ground topography within Chain Valley Bay. For topographic work narrowly focused clear light is generated with a laser and beamed down to earth. A receiver unit is located on an aircraft and collects the returning laser pulse energy reflected from land or water and is recorded in time. The ground topography can be recorded because LIDAR collects multiple returns that are separated based on local relief (Jensen, 2007). The exact location of the LIDAR laser is accomplished using Differential Global Positioning Systems (DGPS). A DEM map layer was created by converting the bare earth layer into multipoint and using TIN interpolation tools in ESRI ArcGIS.

The Lidar data was sourced from the NSE Government Department of Planning who conducted extensive high resolution terrain mapping of the NSW Central and Hunter coasts for the assessment of potential climate change impacts (Department of Planning, 2008). The Lidar was used to derive a 2 m resolution DTM ESRI GRID that included all ground elevation returns with no non-ground features. The lidar returned a ±0.15 m vertical accuracy and ±0.6 m horizontal accuracy. The lidar fly over was conducted by Fugro Spatial Solutions Pty Ltd and was undertaken in January 2007. The DEM created using this data therefore has a vertical accuracy the same as the lidar data and would have 2 m resolution.

The elevations for each vegetation zone through time was calculated using ESRI ArcGIS. Vegetation polygons were converted to raster and zonal statistics were calculated to represent the elevation dynamics for each vegetation zone before and following rapid inundation.

1.16.2 RTK-GPS positioning

Real Time Kinematic (RTK) is a method commonly used in surveying to improve accuracy by the use of carrier based ranging as opposed to code-based position used by a GPS (Novatel, 2014). A RTK instrument was used on site to obtain geographic position and elevation in xyz file format at those core locations that could be accessed by land. The purpose of collecting RTK-GPS values was to validate the efficacy of the DEM at core locations and to obtain more accurate positioning of core locations. These values were compared to values obtained from the DEM in the exact same location to additionally determine if there are any difference in elevation from 2007, the year the DEM was sourced, to 2014. The DEM and interpretations were verified with aerial photographs and field observations. The RTK has a ±1-2 cm horizontal accuracy and a vertical accuracy of ±2-4cm.

Figure 4-1 Real Time Kinematic (RTK) positioned to collect xyz data at Chain Valley Bay, Lake Macquarie for the purpose of obtaining geographic positions and elevations at core locations.

1.16.3 Bathymetry

Data obtained from the Office of Environment and Heritage (OEH) was used in the interpolation of data to show bathymetry. The data was collected between July 2010 and March 2012 as part of the OEH Estuary Management Program. The data obtained by surveyor S.Holtznagel was collected using a RTK GPS, Odom Echotrac MKIII echosounder and had a resolution of 100 m and accuracy of ± 0.18 m (Oceanscan, 2014).

Vector points obtained from an xyz file of Lake Macquarie containing geographic positions and elevations were interpolated by the use of a Triangulated Irregular Network (TIN) in ESRI ArcGIS. The data set was transformed using the nearest neighbour technique (also known as Delauney Triangulation). Nearest neighbour generally produces better results than other interpolation techniques, in terms of accuracy and aesthetics. It should be recognised using the TIN method creates some issues because it assumes a linear relationship between points and this may not be entirely accurate.

Bathymetry data obtained between 2010 and 2012 provides benthic morphodynamic information, in particular the elevation of previously vegetated areas at Chain Valley Bay, and provides insight into the sediment dynamics around the wetland.

1.17 **Accretion and Carbon Store**

1.17.1 Sample Collection

Examination of historic aerial photography identified five inundation classes based on vegetation zonation but was reduced to four after field reconnaissance. They include submerged vegetation area which had been previously heavily vegetated in 1984, mangrove, saltmarsh and mixed forest on the southern side of the path through the wetland (Figure 4-2). Two transects were established that dissected each zone (Figure 4-3). Previous mapping of Lake Macquarie have used similar vegetation mapping units where mangrove and saltmarsh were distinguished from each other (Creese et al., 2009).

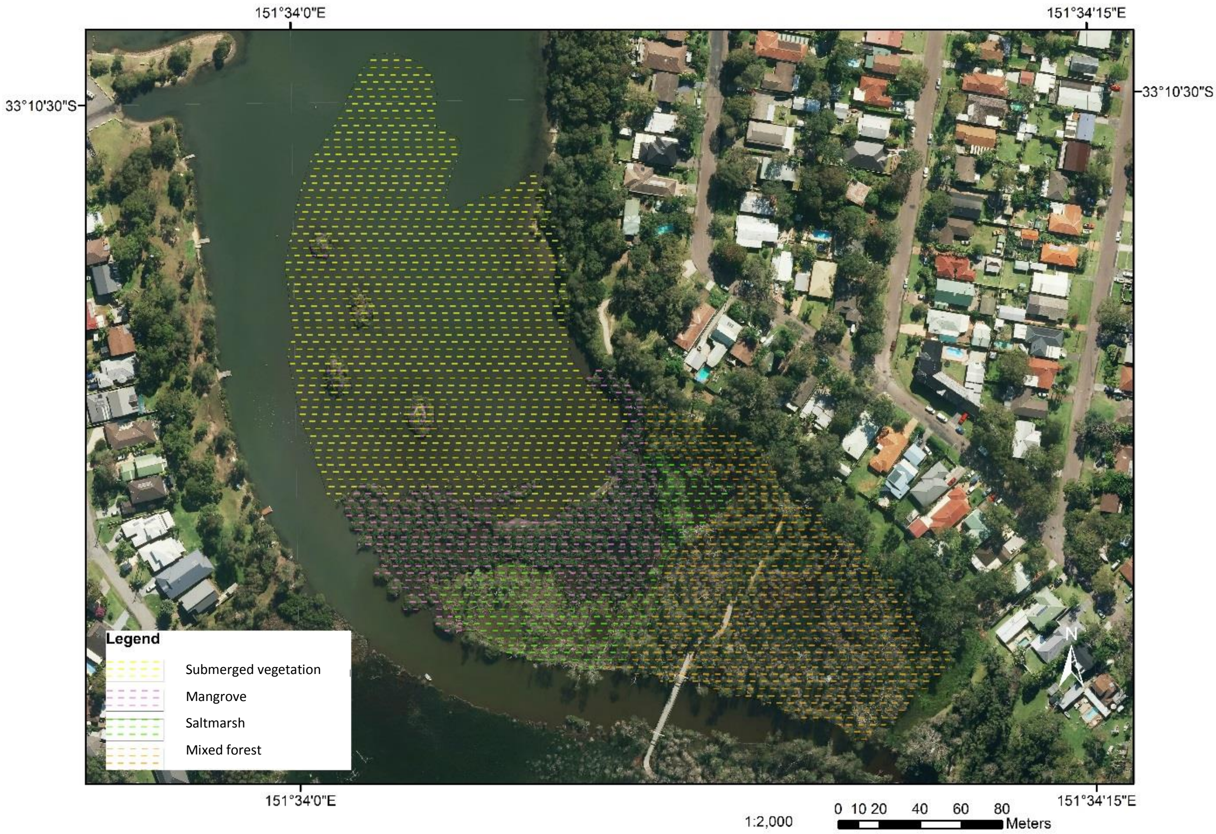


Figure 4-2 Chain Valley Bay Wetland distribution of mangrove, saltmarsh mixed forest and submerged vegetation in 2014. This map was used for plotting core locations.

A team from the University of Wollongong (UOW) attended the study site on the 8th and 9th of September 2014. Two cores were extracted from the mangrove and submerged zones along transect 1 for further analysis of sedimentation rates at the Australian Nuclear Science and Technology Organisation (ANSTO), located at Lucas Heights, NSW Australia (Figure 4-3). An additional nine cores were extracted for analysis of carbon content and carbon source dynamics at ANSTO from transects 1 and 2.

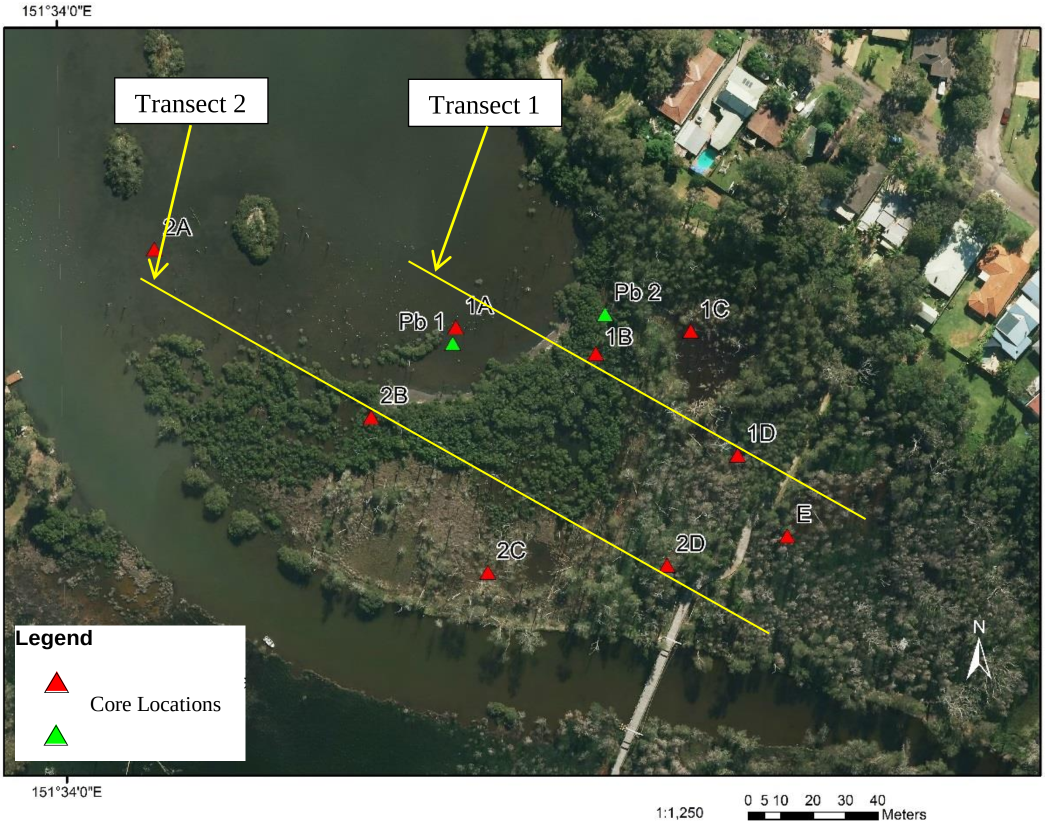


Figure 4-3 Core locations at Chain Valley Bay and transects 1 and 2 of which cores were collected along on the 8th and 9th September 2014.

Care was taken during the extraction to minimise compaction. Sharpened aluminium tubes of approximately 1.3 m in length and 55 cm in diameter were gently hammered vertically into the wetland surface. The A-frame pulley and manual extraction techniques were used to remove cores from the wetland.

Figure 4-4 (a) and (b) below show the extraction techniques at the site including the two person extraction method and the A-frame pulley system that was launched off the side of a boat. The additional nine cores were collected in each identified vegetation zone (Figure 4-2).

One core was taken from the mapped submerged vegetation area, mangrove, saltmarsh and mixed forest in each transect and one additional core was collected from the back of the wetland on the southern side of the foot path running through the wetland (Figure 4-3).
Cores were assigned labels and correspond to the vegetation zone outlined in Table 4-1.

(a)

(b)

(c)

Figure 4-4 a) The A frame pully system of removing sediment cores used at Chain Valley Bay. The tripod is launched off the boat and the core is hammered into the ground and a suction plug is added to the top before being pulled up. b) The core removal technique used on land at Chain Valley Bay. The core is hammered into the ground and the suction plug is added to the top of the core before a clamp is attached and the core is gradually wiggled out. c) Cores were cut open on site and subsampled before being placed directly in a 3-5ºC cold storage box.

Mangroves and saltmarshes often have organic rich soils that range from 10 cm to over 3 m in depth. A minimum depth of 1 m is the recommended standard for accurately quantifying soil carbon pools (Fourqurean et al, 2014). Soil scientists have suggested 30 cm core depth is enough before reaching recalcitrant carbon but the depth of carbon is highly dependent upon evolution and site specific factors. Observations of significant seagrass wrack accumulation was evident along the front shoreline of the wetland.

Table 4-1 The assigned labels to each core within Chain Valley Bay and the vegetation zone and transect they are located within.

Core Identification Label	Transect	Vegetation Zone
1A	1	Submerged area
1B	1	Mangrove
1C	1	Saltmarsh
1D	1	Mixed Forest
E	1 & 2	Mixed Forest
2A	2	Submerged area
2B	2	Mangrove
2C	2	Saltmarsh
2D	2	Mixed Forest
Pb 1	1	Submerged core assigned for ^{210}Pb analysis.
Pb 2	1	Mangrove core assigned for ^{210}Pb analysis.

The nine cores assigned for carbon isotope analysis from each location were cut open and sliced in half and then subsampled in the field (Figure 4-4 (c)). A 2 cm slice was removed from 0-2 cm and 5-7 cm and then every 10 cm down the core to the bottom. Each core half was assigned half A or half B and samples were labelled appropriately and immediately put into a portable fridge set at 3-5ºC to prevent decomposition of organic carbon and diagenesis of stable carbon isotopes. The remaining soil in the cores was not removed and the cores were placed in cold storage. The two cores assigned for accretion analysis using Pb-210 dating techniques were also put in cold storage for later sub-sampling.

1.17.2 Vertical Accretion

In order to determine mass accumulation and accretion rates through time within two cores at Chain Valley Bay radiometric isotope lead-210 (^{210}Pb) dating was used. ^{210}Pb was chosen as an aging technique for the Chain Valley Bay sediments because of its ability to be retained in soils and the adequate half-life for testing sediments within 100 years (Appleby, 2008). Isotope ^{137}Cs was not used because its half-life was too short. Samples from core 'Pb 1' and 'Pb 2' were sliced at laboratories located at the University of Wollongong, NSW. The sediment was sampled from 0-30 cm at every 1 cm and were weighed and placed in a 60ºC oven for 2 days or until dry (Figure 4-5). Samples were reweighed and the bulk density was calculated using Equation 1 below and the percentage of was moisture also calculated.

Equation 1

$$\text{Bulk density (g/cm}^3\text{)} = \frac{\text{Dry soil } (M_{\text{Soilds}})}{\text{Total soil volume } (V_{\text{soil}})}$$

(a) (b)

Figure 4-5 (a) Top 30cm of the mangrove core sliced every 1cm and dried in a 60 ºC oven, (b) and the core samples just taken out of the oven and ready to be bagged and labelled to take to ANSTO.

The ^{210}Pb testing of the dry samples was conducted at laboratories located at ANSTO, Lucas Heights, NSW Australia and took place over a week. Eight samples from each core were chosen for analysis based on the position within the core and the amount of sediment available for testing. The selected samples were ground finely at ANSTO to provide a homogenous sample for the ^{210}Pb analysis.

1.17.2.1 Lead-210 ANSTO analysis method

The Environmental Radioactivity Measurement Centre (ERMC) at ANSTO has created a method for the determination of sedimentation rates by the lead-210 method and encompasses sediment preparation pre-analysis and the methods for analysing polonium-210 (^{210}Po) and radium-226 (^{226}Ra) by alpha spectrometry. Sedimentation rates were calculated using Polonium (Po) and Radium (Ra) calculations in the most current ^{210}Pb dating excel spreadsheet at ANSTO. Upon calculating results graphs were created to represent accretion and mass accumulation at the Chain Valley Bay wetland. The graphs were adjusted using the Constant Rate of Supply (CRS) model rather than CIC. CRS suggests continuous source of 210Pb fallout irrespective of any changes in the sedimentation rate and the CIC assumes constant initial concentration. The CRS model initial concentration varies inversely with the sedimentation rate (Appleby, 2008). Following graphing of results sediment information in the mangrove ^{210}Pb core appeared to be missing and a further three samples were sent to ANSTO for analysis in January 2015.

Sediment pre-analysis preparation

Approximately 0.2-2 g of sediment was weighed accurately into a 150 mL beaker and approximately 5000 dpm of ^{133}Ba and 10 dpm of ^{209}Po mixed tracer solution was added. 10 dpm of each tracer is required so the tracer stock usually has a concentration close to 50 dpm/ml or ^{209}Po and 25,000 dpm/g ^{133}Ba so that the addition of 0.2g stock solution weighed by difference to 5 decimal places is sufficient.

In the fumehood, 10-20 mL of 2M HNO_3 was added to each beaker so the whole sample was dispersed and no sample was left on the sides of the beaker. Some samples had a more vigorous reaction likely due to the presence of some carbonate material. Samples were then heated for at least 5 minutes on a hotplate set at 40-50ºC. Samples were cooled and 10 mL of concentrated HNO_3 was slowly added and the sample swirled and then another 15 mL was added. The concentrated HNO_3 was added slowly so no vigorous reaction would occur. Any sample left on the sides of the beakers was rinsed with 2M HNO_3. The samples were then placed back on the hotplate at 60 ºC to digest until they evaporated close to dryness. A few drops of n-octanol was added to those samples that reacted too vigorously and 2M HNO_3 was used again to wash down the sides of the beakers. The samples were cooled and 5-10 mL of 10% H_2O_2 added so the sediment was covered and then swirled so there were no bubbles. The beakers were then placed back on the hotplate until the effervescence subsided. Another 5 mL of 10% H_2O_2 was added to the sediments like previously and continued to be added using the same method until the samples became less reactive. The less reactive the samples became the less organic matter is in the samples. The samples started to turn into a lighter colour and those that didn't 30% H_2O_2 was added instead until the lighter colour was achieved. Samples were left to reduce to a smaller volume and then let cool. 10 mL HNO_3 and 30 mL of HCl was added to each beaker and placed back on the hotplate with a watchglass. The HCl is added to produce an aceotrope (constant boiling point acid composition) to dissolve all authigenic phases, for example sulphides and carbonates, and to leach the surface of clays and primary minerals. The beakers were left overnight on a hotplate at 50ºC to reflux. Samples were found to be digested sufficiently if the residues appeared light (creamy grey) and the supernatant was yellow (not brown). Lighter coloured samples are thought to provide better results.

Cooled samples were then transferred to a 50 mL centrifuge tube using 6M HCL and centrifuged at 4500 rpm for 5 minutes. The supernatants were decanted back into the original beaker and another 15 mL of 6M HCl was added to the samples and shaken to rinse the residues, then centrifuged for another 5 minutes. The supernatant was then decanted again into the beaker and the residues discarded. Samples were then placed on a hotplate at 60 ºC to evaporate to near dry where 10 mL of 6M HCl was used to rinse the beaker walls. The samples were left to evaporate. About 5 mL of concentrated HCl was added and samples were left to evaporate again. This step was done twice as the repeated addition of concentrated HCl makes sure any nitrates are removed. Samples were then left to cool before continuing with the polonium and radium isolation.

<u>Polonium isolation</u>

Samples were placed on a hot plate-stirrer unit and 30 mL of 0.1 HCl and 50 mL of reagent water was added. The samples were stirred between 70-90 ºC and 1mL of 20% ascorbic acid solution was added to reduce Fe(III) to Fe(II) so the sample could eventually be deposited on silver disks. After 3 minutes 100 μL 1.0M citric acid solution was added to oxidising agents complex trace iron and chromium and then 10 mg of Bi^{3+} holdback carrier was added to inhibit autodeposition of Bismuth. Adjust the pH of the samples to 1.5 with concentrated NH_4OH using cresol red indicator. About 1 g of hydroxylammonium chloride was added rapidly to each sample and a polyethylene holder containing a silver disk was immediately floated, and placed at an angle to prevent bubbles forming on the disk surface. A watchglass was then placed on top of sample beakers and left for 4-6 hours to allow the autodeposit of polonium onto the silver disks and the stirrer was set so the disk holders floated without too much rocking. Periodic spinning of the disk was essential to remove bubbles trapped underneath which can result in less that optimal autodeposition and reagent water was added to maintain the volume in the beaker so the solution would not become too acidic.

Once complete the disks were removed and rinsed with reagent water and so that washings were collected in the beaker. Over a separate waste beaker the disks were rinsed with 95% ethanol and placed on a tissue gently so the deposited surface was not touched.

Once dry the disks were labelled and taken for alpha spectrometry to count the prepared disk sources and determine the activity of ^{210}Po.

<u>Radium isolation</u>

The remaining solution from the polonium isolation above was transferred into a 1 L beaker and diluted with approximately 800 mL of reagent water and placed on a magnetic stirrer at a high setting. 20 mL of concentrated H_2SO_4 was slowly added then 100 mL 20% Na_2SO_4. 10 mL of 10mg/L Pb^{2+} carrier in 0.1 HNO_3 was added slowly drop wise from a tube placed above the beaker. The beakers were left overnight and a Pb/Ba/Ra sulphate precipitate formed. The supernatant was decanted slowly to prevent any loss of the precipitate and the precipitate was then centrifuged with 50% ethanol at 5100 rpm for 2 minutes. The supernatant was then decanted and the beaker was washed with 50% ethanol into the centrifuge tube and then centrifuged again. After a second decanting 5 mL of 0.2M Na_5DTPA and 1 drop of thymol blue was added and the tubes were placed in an ultrasonic bath to dissolve all the sulphate precipitate. 2 drops of methyl red indicator was added and the solution turned green. The samples were then passed through a 0.45 μm disposable membrane filter into a polycarbonate vial and 2 mL or 1:1 acetic acid/water and 1 mL $BaSO_4$ seeding suspension which had been ultra-somicated was simultaneously added and the solution turned pink. The vial was then placed in cold water for 30 minutes and then passed through a smooth surfaced Millipore "VV" membrane filter in a lock-seal Gelman filter apparatus with 50% ethanol. The colloidal Ba/Ra sulphate precipitate was swirled before being added and the vial and filter funnel walls rinsed thoroughly to ensure all the precipitate collected on the filter. The filter was placed in a petri dish and placed on top of a HPGe gamma detector where gamma spectrum was collected for 10 minutes measuring the recovery of ^{133}Ba via the 356 keV peak. Each filter was then stuck onto a carbon tab and ^{226}Ra was analysed by alpha spectrometry.

1.17.3 Sediment Characteristics

Sediment characteristics, colour and texture were recorded soon after the opening of each core. Samples were then analysed for bulk density, % moisture and grain size at the

University of Wollongong, NSW Australia. Samples already sub-sampled in the field and stored in cold storage at 3-5 ºC were removed for bulk density analysis similar to that seen in Figure 4-5 (b). The sediment samples were weighed and then placed in a 60 ºC oven for at least 2 days and then reweighed and bulk density (g/cm^3) calculated using equation 1. Dried samples were then ground to a fine powder (< 250 μm) using a Retsch vibrator mill so they could then be used for carbon isotope analysis. Particle size analysis of all subsamples was conducted at UOW on the Malvern Mastersizer 2000 on wet samples and gave values for sand, silt and clay content. Gravel content was deduced visually as the sediment was too large for the Mastersizer. Results were graphically represented together with carbon isotopic results and % carbon.

1.17.4 Carbon dynamics and sources

In order to determine carbon isotopic signatures and the percentage of carbon within the cores sampled from Chain Valley Bay, samples were prepared at the University of Wollongong and ANSTO, and eventually analysed using dry combustion at ANSTO.

Dried and ground samples were acid washed once using 1M HCl to remove carbonate material from the subsamples. Samples were left for approximately 2 days or until the reaction had stopped and then placed in a centrifuge for 3 minutes. The acid was then decanted and samples were then rinsed using RO water and placed back into the centrifuge and again decanted. Samples were transferred to tin trays using RO water and placed in a 60ºC oven for 2 days, or until water had evaporated.

Carbonate material was not fully removed from samples 65 cm and down in the core, therefore only carbon isotope and carbon percentage results from 0 – 55 cm will be considered in this study. All sub-samples from transect 1 were analysed for carbon and only subsamples 0-2, 5-7, 15-17, 25-27, 45-47, 65-67, 85-87, 105-107cm from transect 2 were analysed for carbon.

The finely ground acid washed samples were taken to ANSTO and were weighed and pelletised in small tin capsules over 3 days and then analysed with a continuous flow isotope ratio mass spectrometer (CF-IRMS); model Delta V Plus (Thermo Scientific Corporation, USA), interfaced with an elemental analyser (Thermo Fisher Flash 2000 HT EA, Thermo Electron Corporation, USA). In summary the sample is combusted into CO_2 in a combustion furnace (silvered cobaltous/ic oxide, chromium oxide, quartz chips and quartz wool) at 1020 ºC and then transferred to a helium carrier gas (100 mL/min) into a copper reduction furnace at 600 ºC, where any excess O_2 is removed. The analyte gases are then passed through a water trap before the CO_2 are separated by a Gas Chromatography column at 40 ºC and then are transferred to the mass spectrometer for $\delta^{13}C$ measuring.

Some samples needed to be reweighed after the initial run through because they were found to be either too small or too big to allow carbon to be determined.

Values were reported according to IAEA secondary standards that have been certified relative to VPDB for carbon. Data was normalised using a two point calibration, utilising standards that bracket the samples being analysed. To maintain quality control three references were also included in each run these being Sercon SC0419, USGS-40 L-Glutamic acid and USGS-41 L-Glutamic acid. The results obtained are accurate to 1% of the actual value for % C and ± 0.3 permil for $\delta^{13}C$ values. The carbon isotope ratios are reported as $\delta^{13}C$ values, which were calculated using Equation 2.

Equation 2

$$\delta^{13}C = \frac{R\,({}^{13}C/{}^{12}C)_{sample} - R({}^{13}C/{}^{12}C)_{reference}}{R\,({}^{13}C/{}^{12}C)_{reference}}$$

The % carbon and $\delta^{13}C$ results were graphed together with sediment characteristic results. Carbon volume ($C.g/cm^3$) was also graphed with results and was calculated by multiplying bulk density and % carbon.

The separation of $\delta^{13}C$ into carbon sources was based on marine vegetation, carbonate material, terrestrial vegetation and terrestrial/marine vegetation and is represented in Table 4-2 below. Each vegetation was assigned a C3 or C4 value based on photosynthetic pathways. Material with lower $\delta^{13}C$ values are generally located in marine areas, for example seagrass. Although seagrass is a C3 species, it commonly reflects C4 pathways due to absorbing carbonates HCO^{3-} from the water column hence their lower isotopic signature. Previous studies have used carbon isotope signatures to record the change in carbon sources (Saintilan et al., 2013; Choi et al., 2001).

Table 4-2 Marine and Terrestrial carbon sources possible at Chain Valley Bay and their carbon 13 isotopic signature and vegetation classification.

	Vegetation/Carbon Source	$\delta^{13}C$	C3 or C4	Source
Marine vegetation	*Zostera capricornia*	-10.8 ± 2.3 - 11.7	C3 (reflects C4)	Hemminga & Mateo 1996 Guest et al. 2004
	Posidonia australis	-9.9	C3 (reflects C4)	Hemminga & Mateo 1996
	Halophila ovalis	-10.0	C3 (reflects C4)	Hemminga & Mateo 1996
Carbonate Material	*Anadara trapezia*	Approaching 0 (0.3, -0.8)		Sean Ulm 2006
Terrestrial vegetation	*Avicennia marina*	-24 (leaf)	C3	Rogers, per comm. (from Cararma Inlet)
		-24 (stem)	C3	Rogers, per comm. (from Cararma Inlet)
		-28 (leaf)	C3	Saintilan et al. 2003
		-24 (roots)	C3	Saintilan et al. 2003
	Juncas kraussii	-27	C3	Saintilan et al. 2013, Rogers, per comm. (from Cararma Inlet)
	Casuarina glauca	-30	C3	Piola et al. 2008
	Melaleuca quinquenervia	-31	C3	Piola et al. 2008
Terrestrial/ marine vegetation	*Sporobolus virginicus*	-15, -17, -18	C4	Saintilan et al. 2003, Rogers, per comm. (from Cararma Inlet)

1.18 **Chapter Summary**

The subsidence at Chain Valley Bay from 1986 onwards can be used as a surrogate for rapid sea level rise. Spatial analysis of vegetation from 1984 to 2014 was used to determine changes in vegetation size and zonation due to inundation. Wetland morphology analysis was undertaken using DEM and bathymetry mapping in conjunction with RTK-GPS elevation data. All spatial analysis and wetland morphology analysis was undertaken using ESRI's ArcGIS version 10.2. Accretion and carbon store analysis was undertaken over many months. Cores were collected in September 2014 and vegetation zones defined. Vertical accretion was determined using radiometric isotope ^{210}Pb dating and was prepared and then analysed at ANSTO using alpha spectrometry. Sediment characteristics of the Chain Valley Bay wetland including colour, texture, bulk density, percent moisture and grain size were determined at the University of Wollongong, NSW Australia. Dried sediments were ground finely and acid washed to remove carbonates. Carbon dynamics and sources were determined for acid washed sediments by analysis using the CF-IRMS machine at ANSTO. Carbon percentage and $\delta^{13}C$ values were reported and carbon volume calculated (C. g/cm^3). Carbon isotopic signatures from previous studies were used to identify carbon sources within the cores.

5. RESULTS

Variations in vegetation extent, the existence of remnant wetland in submerged areas and elevation data within the wetland was analysed using spatial analysis techniques on aerial photography, xyz data, Lidar and field GPS points. Using chronology isotopic techniques changes in accretion in submerged and mangrove areas of the wetland through time were found as was the change in mass accumulation. Combined with carbon isotopic results and a characterisation of the sediments found in 1 metre cores, the changes in carbon sources and the percentage of carbon was observed before and after the inundation of the wetland. This chapter presents vegetation succession, morphodynamics, accretion and carbon storage information with the Chain Valley Bay wetland.

1.19 **Vegetation Dynamics**

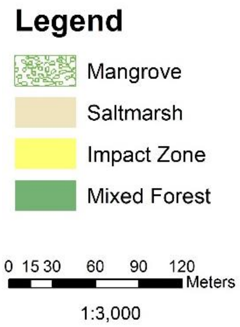
Vegetation within Chain Valley Bay were categorised into four groups: mangrove, saltmarsh, mixed forest and impact zone. Each zone was based on dominant vegetation and shifts in vegetation over time provide an indication of inundation within the wetland following the removal of pillars within the long wall mine located under the wetland in 1986 which caused the mine to collapse. The changing vegetation since 1984 to 2014 is represented in Figure 5-1 to Figure 5-10. A summary of the vegetation mapping is provided in Table 5-3 and the change in area of each vegetation zone through time is provided in (Table 5-1)

In 1984 the dominate vegetation zone was mixed forest which is characterised by *Casuarina glauca* and *Melaleuca quinquenervia* tree species and had an approximately area of 39 000 m^2. Some saltmarsh is behind mangrove areas and boarded by mixed forest. Uncertainty surrounds the mapping of saltmarsh in 1984 imagery as the areas of standing water level are assumed to be natural tidal inundation of the saltmarsh rather than subsidence. In 1984 no subsidence had been recorded at the site.

In 1986 the Chain Valley Bay wetland and its surrounds started to encounter lateral and vertical subsidence due to a collapse in the underground long wall mine operating underneath. Approximately 500 mm of subsidence was recorded. Little change in vegetation occurred between 1986 and 1984 and mixed forest dominated followed by mangrove and saltmarsh. Some small sections of saltmarsh areas appear in 1986 but not in 1984 and is due to the quality of the 1984 aerial photograph. It should be assumed no change in vegetation has occurred in the two year period.

1984

Figure 5-1 Aerial photography and spatial vegetation mapping of the Chain Valley Bay wetland in 1984.



1986

Figure 5-2 Aerial photography and spatial vegetation mapping of the Chain Valley Bay wetland in 1986.

Following the mine collapse in 1986 evidence of impacts on the wetland only became apparent in 1987 when vegetation started to die. The previous year in 1986 the dominate vegetation was mixed forest which extends from the back of the wetland to the northern section. The mangrove forest had a large extent at the entrance of the wetland and was adjacent to small saltmarsh sections and small depressions suffering small inundation likely controlled by tides. The first areas to suffer death were small sections of mangrove located at the northern point of the wetland and became evident in the 1987 imagery.

In 1990 a large zone of impact (approximatly 30 000 m^2) was identified on the imagery. Numerous dead tree trunks from the mixed forest are evident as are dead mangrove trees at the front section of the wetland. The sudden and rapid loss of vegetation within the three year period from 1987 to 1990 would have been caused by the rapid permanent inundation of water which caused the site to no longer be intertidal and therefore not support mangroves for an extended period of time. The mangrove pneumatophores would have attempted to counter inundation by extending vertically in response to water level increase but as the increase was rapid this response would have proven ineffective. A small section of mangrove remained as did some mixed forest towards the back of the wetland.

1987

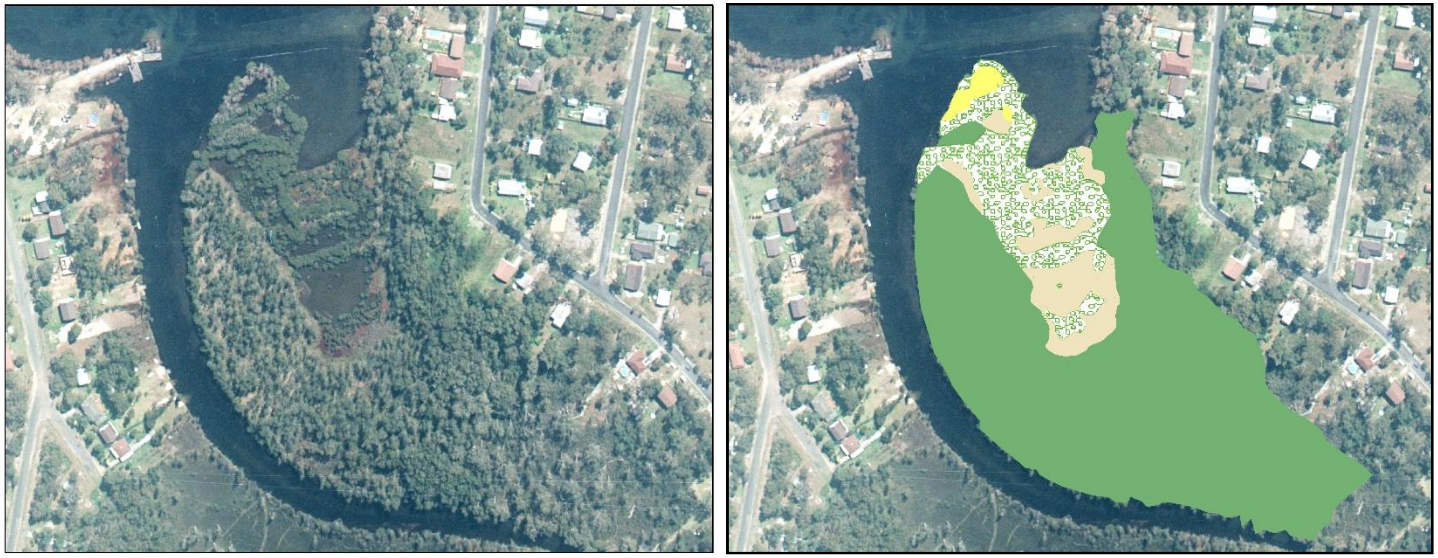
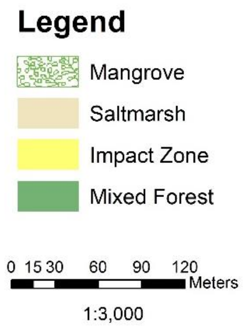


Figure 5-4 Aerial photography and spatial vegetation mapping of the Chain Valley Bay wetland in 1987.



1990

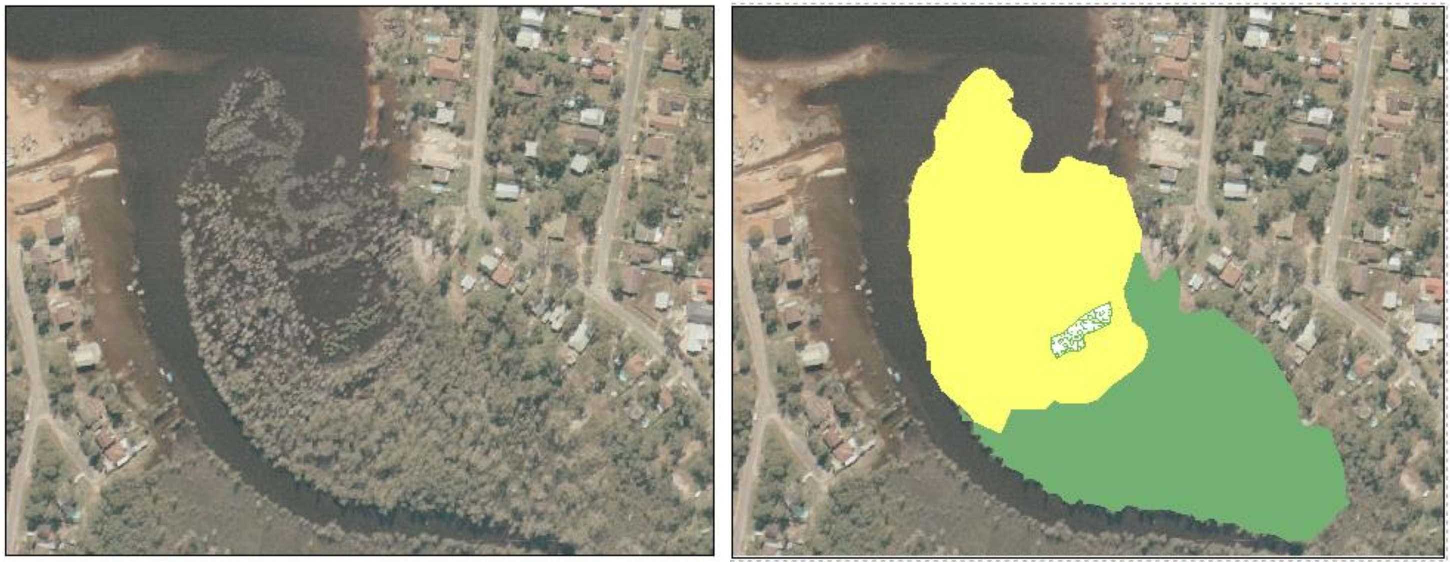


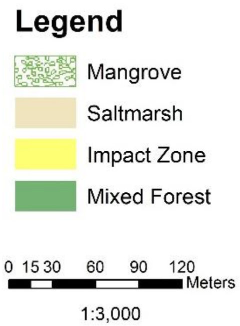
Figure 5-3 Aerial photography and spatial vegetation mapping of the Chain Valley Bay wetland in 1990.

In 1996 the front section of the wetland no longer in existed and was now completely inundated. The zone of impact to appears smaller in 1996 because the wetland is no longer visible and there has also been a reduction in the amount of visible dead vegetation. The zone of impact extends further back into the mixed forest area where trees would have slowly died because they were not suffering permant inundation conditions like the mixed forest area at the front of the wetland and would likely undergo less tidal impacts. Small hillocks appear at the front of the wetland in 1996 and are thought to be the remaining pillars in the collapsed mine under Chain Vally Bay. The small mangrove area in the centre of the wetland has also died which could suggest the mine was still slowly subsiding from 1990 to 1996 and only fringing mangrove remains on the water channel to the south-east of the wetland.

In 2003 the zone of impact is still extensive although mangrove started to recolonise the front of the wetland and small sections of saltmarsh appear behind the mangrove. Over the next three years mangrove and saltmarsh zones extend into the impacted zone which suggests the wetland is trying to adapt to the new iundation regime.

1996

Figure 5-5 Aerial photography and spatial vegetation mapping of the Chain Valley Bay wetland in 1996.



2003

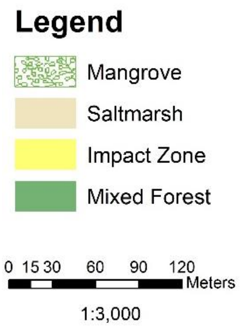
Figure 5-6 Aerial photography and spatial vegetation mapping of the Chain Valley Bay wetland in 2003.

In 2006 the extent of saltmarsh and mangrove vegetation has increased and areas of impact located at the back of the wetland have been recolonised with some mixed forest vegetation. The mangrove is surviving on the new shore line of the wetland and saltmarsh areas are returning behind mangrove.

In 2010 the recovery becomes more apparent with more saltmarsh and mangrove area and sections of the mixed forest also starting to recover. The zone of impact is completely gone in the 210 imagery. Saltmarsh vegetation has replaced most of the zone of impact and mangove and mixed forest have colonised on the boarder of the large impact zone.

2006

Figure 5-7 Aerial photography and spatial vegetation mapping of the Chain Valley Bay wetland in 2006.



2010

Figure 5-8 Aerial photography and spatial vegetation mapping of the Chain Valley Bay wetland in 2010.

Between 2010 and 2014 mangrove incursion landward south-east into saltmarsh habitat occured and as a result a loss in saltmarsh area was observerd. Observations made at the site show the growth of young *Avicennia marina* seedlings in gaps along the edge of the current mangrove zone bordering saltmarsh areas (Figure 5-9). Mixed forest vegetation also appears to be encroaching on saltmarsh areas by moving north-west.

Figure 5-9 *Avicennia marina m*angrove seedlings growing on the edge of the current mangrove area within gaps.

2014

Figure 5-10 Aerial photography and spatial vegetation mapping of the Chain Valley Bay wetland in 2014.

The wetland has undergone rapid inundation causing large vegetation death due to subsidence caused by a collapse in the long wall mine underneath. From 1984 when the mine collapsed to 2014 there has been a decrease in mangrove extent of -0.9% per year, an addition in saltmarsh extent of 8.2% per year and a decrease in mixed forest by -2.6% per year (Table 5-1). The wetland is still recovering from inundation and these values may change through time if the mangrove and mixed forest incursion into saltmarsh areas continue. A gradual decline in mixed forest zone is seen in

Figure 5-11 from 1986 to 2010. From 2010 to 2014 area slightly increases at a rate of 18.3% per year. The impact zone appears in 1990 and gradually declines in extent until 2010. Mangrove and saltmarsh areas follow a similar pattern. Vegetation death occurs in 1990 and doesn't return until 1996. From 1996 to 2010 both mangrove and saltmarsh increase in area until reaching approximatly 7500 m^2 where saltmarsh starts to decline towards 2014 and mangrove and mixed forest increase slightly.

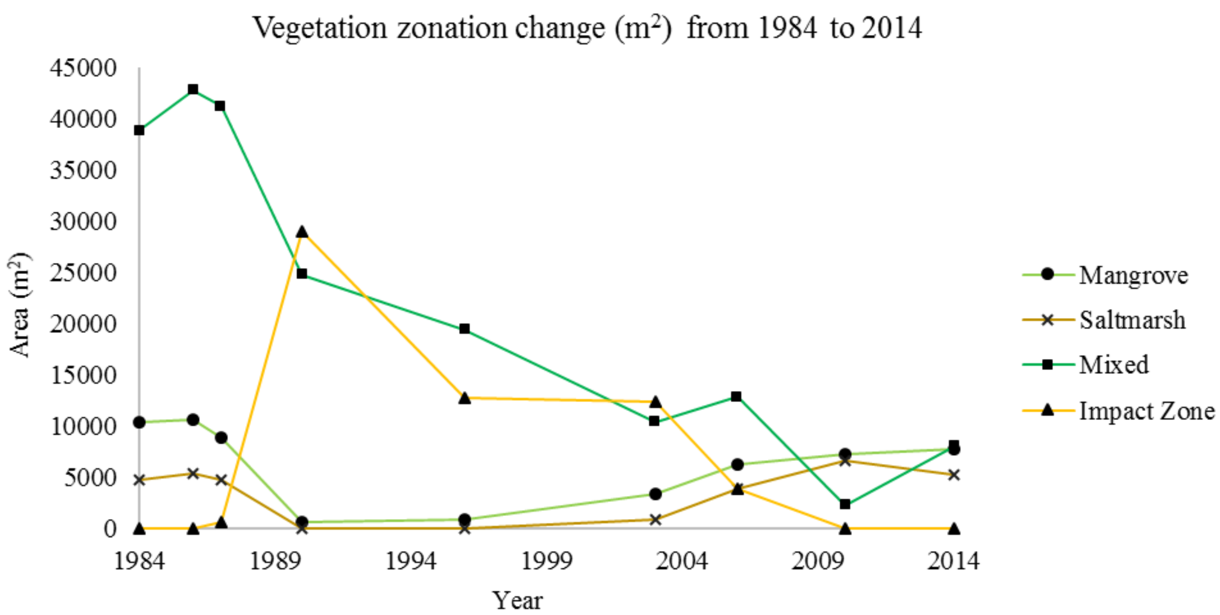


Figure 5-11 Vegetation area change (m^2) in the Chain Valley bay wetland from before inundation to 2014.

Table 5-1 Vegetation change and rate of change through time for available time periods.

Study Period	Vegetation	Area at time 1 (m^2)	Area at time 2 (m^2)	Change (%)	Rate of change (% yr^{-1})
1984-1986	Mangrove	10416	10643	2.2	1.1
	Saltmarsh	4809	5382	11.9	5.9
	Mixed Forest	38873	42846	10.2	5.1
1986-1987	Mangrove	10643	8854	-16.8	-16.8
	Saltmarsh	5382	4809	-10.6	-10.6
	Mixed Forest	42846	41269	-3.7	-3.7
1987-1990	Mangrove	8854	680	-92.3	-30.8
	Mixed Forest	41269	24803	-39.9	-13.3
	Impact Zone	1905	29067	1425.9	475.3
1990-1996	Mangrove	680	876	28.8	4.8
	Mixed Forest	24803	19479	-21.5	-3.6
	Impact Zone	29067	12744	-56.2	-9.4
1996-2003	Mangrove	876	3432	292.0	41.7
	Mixed Forest	19479	10436	-46.4	-6.6
	Impact Zone	12744	12385	-2.8	-0.4
	Saltmarsh	0	946		
2003-2006	Mangrove	3432	6239	81.8	27.3
	Mixed Forest	10436	3851	-63.1	-21.0
	Saltmarsh	946	3851	307.1	102.4
	Impact Zone	12385	12910	4.2	1.4
2006-2010	Mangrove	6239	7280	16.7	4.2
	Mixed Forest	3851	6665	73.1	18.3
	Saltmarsh	12910	2315	-82.1	-20.5
	Impact Zone	3892	0	-100.0	-25.0
2010-2014	Mangrove	7280	7753	6.5	1.6

	Mixed Forest	6665	5303	-20.4	-5.1
	Saltmarsh	2315	8062	248.3	62.1
Overall (1984-2014)	Mangrove	10416	7753	-25.6	-0.9
	Saltmarsh	4809	5303	10.3	8.2
	Mixed Forest	38873	8062	-79.3	-2.6

Following the rapid iundation, within 10 years there was no impact zone and mangrove, saltmarsh and some mixed forest vegetation have provided rehabilitation of the wetland.

During site visits to the wetland in 2014 remnant dead vegetation was still observed throughout all vegetation areas (Table 5-2). Mixed forest vegetation *Casuarina glauca* were observed to be present randomly throughout some areas of the saltmarsh zone which could indicate brackish water source perhaps from groundwater.

Table 5-2 Photographs taken on the 18th December 2014 (a) showing remnant dead tree trunks previously of the mixed forest but now within saltmarsh (b) left- remnant dead tree trunks in the submerged area of the mangrove at the front of the wetland, right- small Casuarina trees within the mixed forest zone with a species of wetland grass underneath. (c) mangrove areas previously populated by paperbark trees (*Melaleuca quinquenervia*) which only exist now as dead tree trunks.

(a)

Swampy saltmarsh	***Saltmarsh***
	

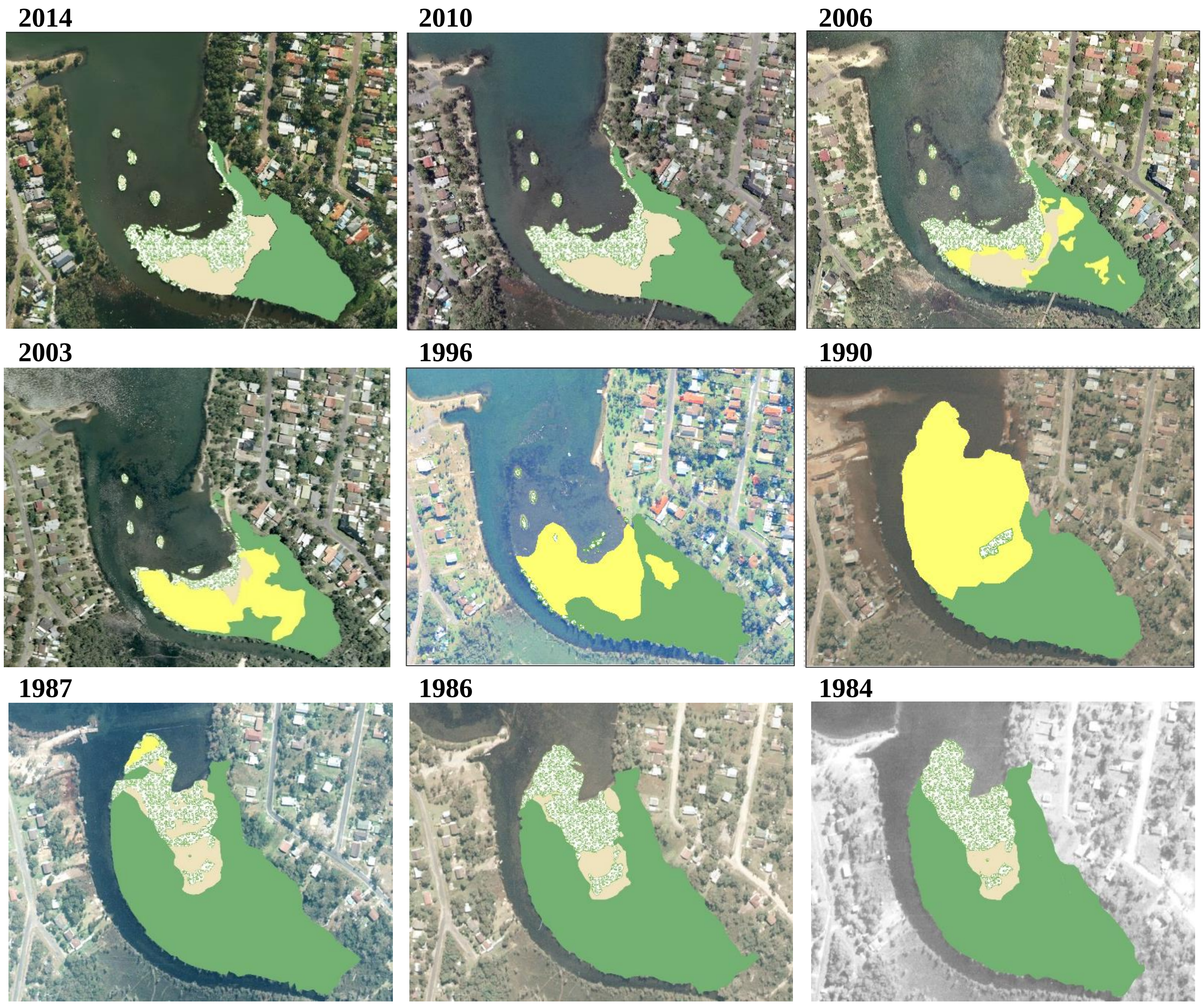
(b)

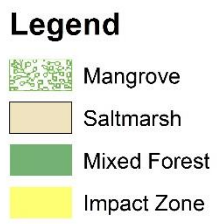
Submerged mangrove in front of the wetland	*The back of the wetland within the mixed forest*
	

(c)

Mangrove	*Mangrove*
	

Table 5-3 Vegetation zonation change through due to rapid inundation.





1.20 **Wetland morphodynamics**

1.20.1 Digital elevation model (DEM)

The lidar derived DEM provides bare earth elevation of the Chain Valley Bay wetland in 2007 (Figure 5-12). Elevation data provided by the DEM was used in conjunction with zonal statistics to provide likely elevations of vegetation zones through time from 1984 to 2014. Figure 5-12 below gives an indication of the lower elevation within the wetland area compared to nearby houses and streets. The elevation of the wetland is between 0 and 1.4 m and shows a general transition from high elevation values at the back of the wetland to low elevation values north-east towards the shoreline.

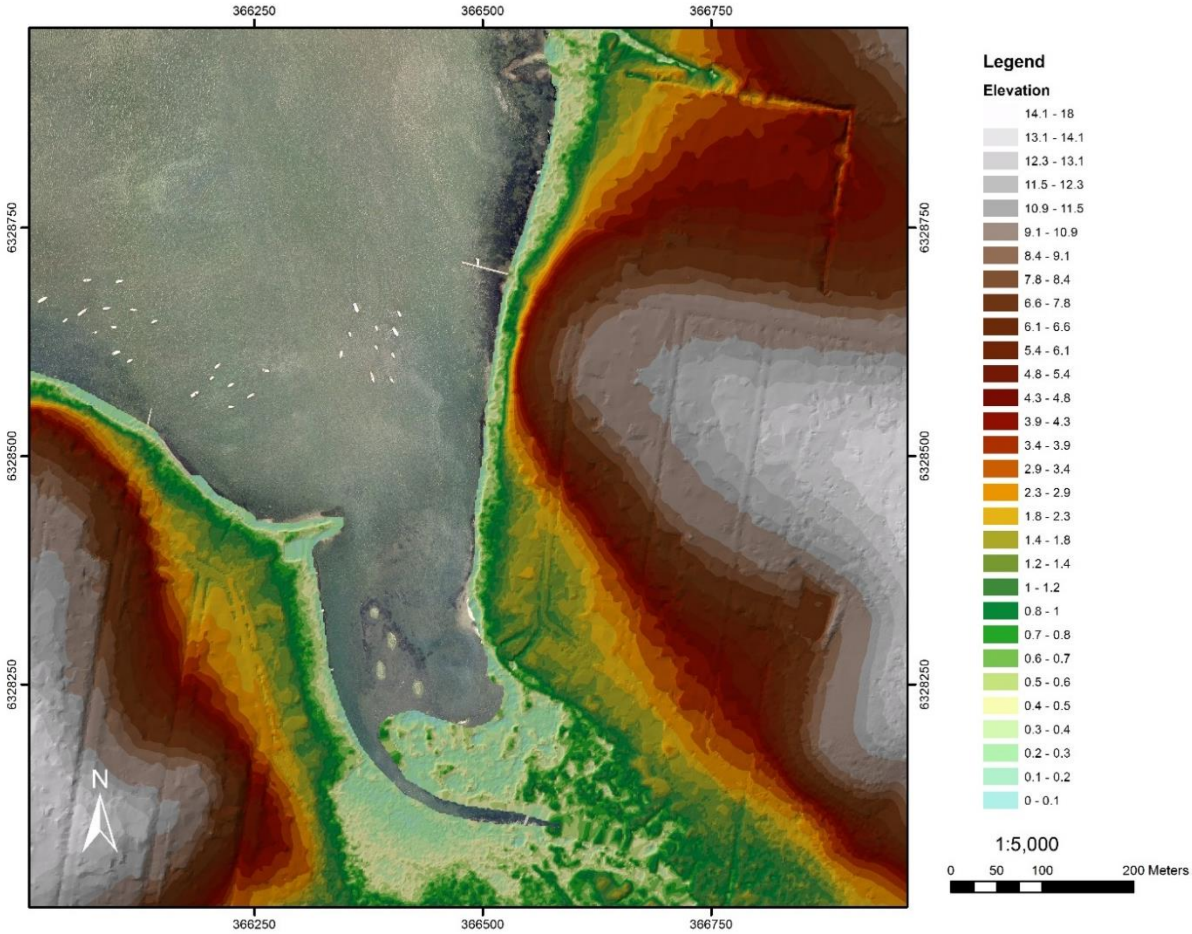


Figure 5-12 DEM of the Chain Valley Bay wetland derived using Lidar data collected in 2007.

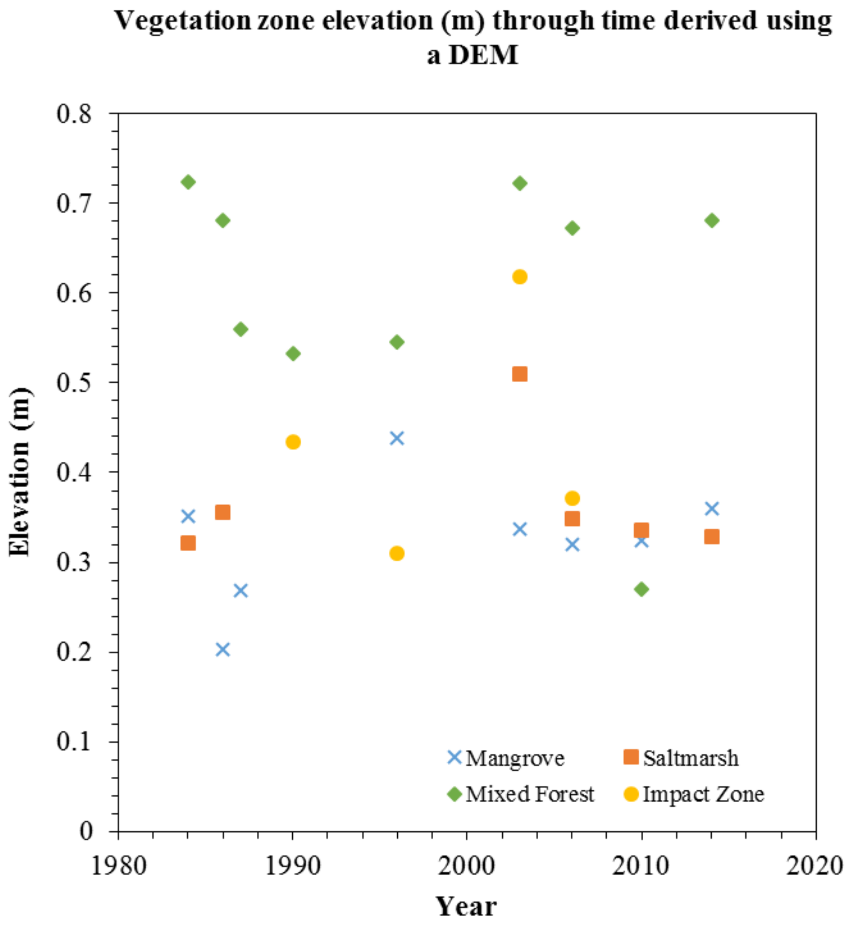


Figure 5-13 Elevation (m) of vegetation zones through time derived using a DEM created using Lidar collected in 2007.

Vegetation zone elevation through time are estimated through time based on DEM sourced for one year (2007) and should be used as a guide for elevation values. Elevations predicted using the DEM provide characteristic elevations for wetland vegetation for those areas the Lidar has been gathered. Some older vegetation zones could not have elevation calculated because they were inundated in 2007.

In Figure 5-13 the mixed forest zone has highest elevation values and range between 0.52 m and 0.72 m. A decrease in elevation appears to have occurred following inundation from 1986 but increases again in 2003, and remains around 0.7 m elevation. Saltmarsh and mangrove elevation are very similar although mangrove vegetation generally seems to be slightly less. Saltmarsh elevation ranges from 0.32 m to 0.5 m and mangrove elevations range from 0.2 m to 0.6 m. Recent elevation values show saltmarsh and mangrove around similar elevations. Impact zones through time have appeared to fluctuate from 0.3 m to 0.62 m.

RTK-GPS elevations obtained from the wetland in late 2014 have elevations values different to those predicted using the DEM. The mangrove vegetation zone had values ranging from -0.029 m to 0.144 m whilst DEM predicted values for 2014 has a mean elevation of 0.36 m. This could likely be suggesting the 2007 DEM lidar information is not adequate to provide elevations for later years because more subsidence has occurred since or other processes have occurred. There has been a 7 year gap between the time the lidar data was collected and the GPS elevations gathered and elevation gains could have been quickly lost to surface autocompaction or subsurface processes like organic productivity and groundwater flux (Rogers et al, 2006). The elevations recorded in the saltmarsh vegetation zone ranged from 0.03 m to 0.118 m and mixed forest had elevations from 0.22 m to 1.199 m. The very high mixed forest upper range value recorded at core location 2D could be due to the area being above a remaining pillar from the remnant long wall mine underneath the wetland.

The discrepancy between the DEM values in 2007 and the RTK derived values in 2014 are tabulated in Table 5-4 and could suggest subsidence has occurred since 2007.

Table 5-4 Average elevation values were created based on RTK and DEM 2007 elevations and mean elevation defined for the period between 2007 and 2014.

Vegetation Zone/Core ID	**RTK derived Elevation (m) 2014**	**DEM derived Elevation (m) 2007**	**Average of RTK and DEM elevation values (m)**	**Mean elevation (m)**
Mangrove				**0.112**
2B	-0.144	0.376	0.116	
1B	-0.029	0.244	0.1075	
Saltmarsh				**0.153**
1C	0.03	0.221	0.1255	
2C	0.118	0.242	0.18	
Mixed Forest				**0.674**
2D	1.199	1.080	1.1395	
1D	0.247	0.404	0.3255	
E	0.22	0.896	0.558	

1.20.2 Bathymetry

Bathymetry provides information on the current shape and depth of the Chain Valley Bay wetland in areas permantly inundated. There is evidence of the remant wetland that has undergone inundation due to the mine collapse (Figure 5-14).

Aerial imagery from 1894 depecting the submerged area corroborates that a large section of the wetland has become inundated rapidly and it appears some still remains. The highest edge of the remnant wetland that is now permantly inundated has a maxiumum elevation of -0.25m and is now collonised by mangrove. Previously before the mine collapse the area was collonised by mixed forest. The latest elevation levels of the mixed forest zone that have been derived using the 2007 DEM and 2014 GPS data show mixed forest occurs approximately at 0.674 m elevation. If it is assumed these elevations are a characteristic of the mixed forest zone then there has been a reduction in elevation of approximatly -0.924 metres. The fact that sediment still remain is likley due to the wave energy in Lake Macquaire not interacting with the sediments at depth. This is a characteristic of the Lake Macquarie youthful barrier estuary.

The 1984 remant submerged mangrove zone indicated by the dotted line on Figure 5-14, follows the bathymetry contours with elevation -0.75 m. Using the estimated elevation for 0.112m for the mangrove zone, the elevation has reduced by approximatly -0.862 m. The most recent subsidence value for Chain Valley Bay is 0.850 m recorded in 1991. Mangrove areas appear to have contiuned to submerge by 12 mm from 1991. Mixed forest areas have suffered more subsidence since 1991, with a difference of 74 mm.

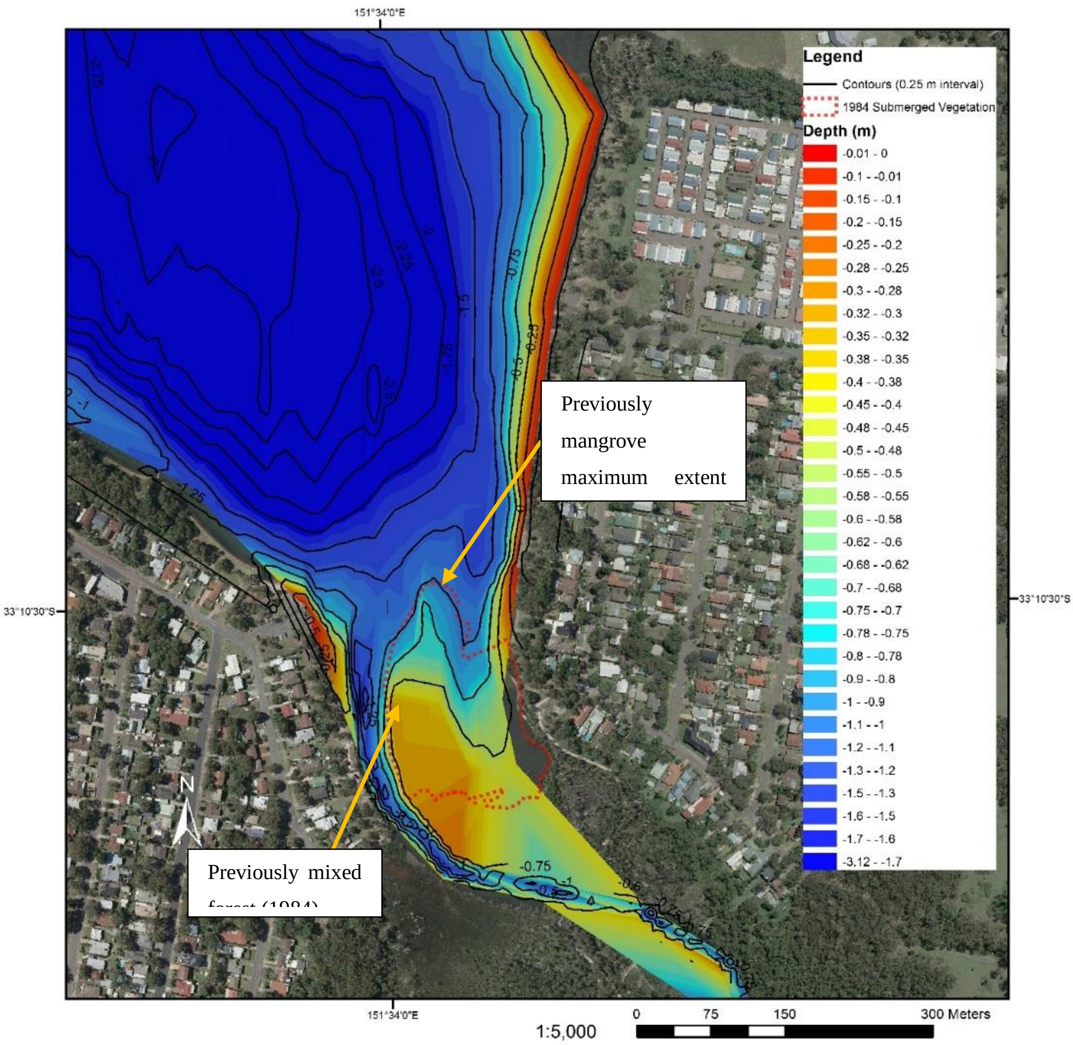


Figure 5-14 Bathymetry at Chain Valley Bay (contour interval 0.25 m). Remnant wetland is evident from before the mine collapse.

1.21 **Vertical Accretion**

1.21.1 Accretion and Carbon Storage

The submerged core (Id: Pb 1) has transitioned from mixed forest to completely inundated and the mangrove core (Id: Pb 2) has transitioned from mixed forest to mangrove and has had no period of sustained inundation like the submerged core. This vegetation transition in the cores can be related to the accretion at the sites where an increase in accretion within the submerged core is recorded following the mine collapse but the mangrove core has remained relatively stable (Figure 5-15).

The accretion trend within the submerged core has always been greater before and following inundation. The submerged core is lower in the inundation profile for the entire period of this study and it is reflected in the accretion values. The accretion trend with the mangrove core has remained relatively stable, with values between 1mm and 3 mm per year. In comparison, there has been a significant increase in accretion within the submerged core following mine subsidence.

The core obtained from the submerged area has accretion occurring at a rate of 3 mm y^{-1} from 1909 to 1979 but this increases in the period of 1979 to 2013 to a value 13 mm y^{-1} and is within the period when inundation occurred. The high accretion values in the submerged zone of the wetland is indicative of rapid carbon sequestration and has implications for carbon storage within the Chain Valley Bay wetland. The submerged areas of the wetland is likely attempting to catch-up and organic matter is being deposited in the space made available possibly due to the removal of organic matter and sediment from the top layer of stratigraphy when inundation occurred. The initial rapid inundation of the wetland could have allowed erosion from wave action to occur. The accretion results show no net loss has occurred since inundation suggesting the wetland is still adjusting.

The little change and only slight decrease in accretion seen in the mangrove core since the mine collapse suggest organic carbon sources have transitioned from one vegetation source to another with no prolonged period of inundation. The mangrove core would likely not have been impacted by wave energy to the degree that the submerged core has because of its position at higher elevation and would therefore have retained most of its below ground carbon.

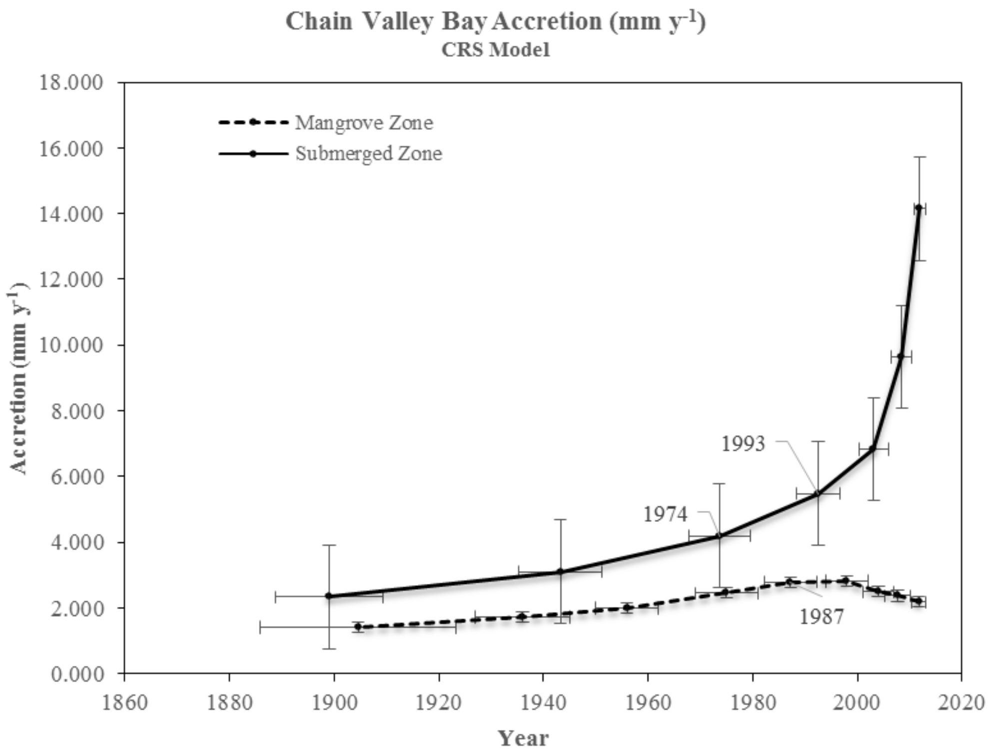


Figure 5-15 Accretion (mm y^{-1}) (±SD) at Chain Valley Bay within mangrove and submerged areas calculated use ^{210}Pb radiometric isotopes.

1.21.2 Mass Accumulation

Cores obtained in the mangrove area and in the submerged area at Chain Valley Bay in 2014 were tested using ^{210}Pb radiometric dating techniques to obtain mass accumulation data from 1905 to 2014 and are represented in Figure 5-16 below.

There has been a steady increase in mass accumulation since approximately 1905 to 1960. A rapid drop in accumulation to 0.06 g $cm^{-2}y^{-1}$ occurs between 1974 and 1979 in both cores. This could be due to the wetland changing from mineral based sediments to more organic based material. A jump in mass accumulation in the mangrove core is seen in 1998 and is likely due to more mass from mineral sediments perhaps in response to accretion. It then declines again until 2004. The mass accumulation in both areas of the wetland increases rapidly around 2003 and 2004. In the mangrove core it moves from 0.09 ± 0.01 g $cm^{-2}y^{-1}$ to 0.14 ± 0.01 g $cm^{-2}y^{-1}$ and in the submerged core it moves from 0.07 ± 0.01 g $cm^{-2}y^{-1}$ to 0.16 ± 0.01 g $cm^{-2}y^{-1}$. This rapid change in mass accumulation following the mine collapse likely indicates a change in sediment type from predominantly organic to mineral based material. IN both cores mass accumulation appears to not be reducing and could indicate the continued accretion of material since inundation. Evidence of inundation in aerial photography and massive vegetation death indicated by the zone of impact corresponds to the likely reduction in the source of organic based material.

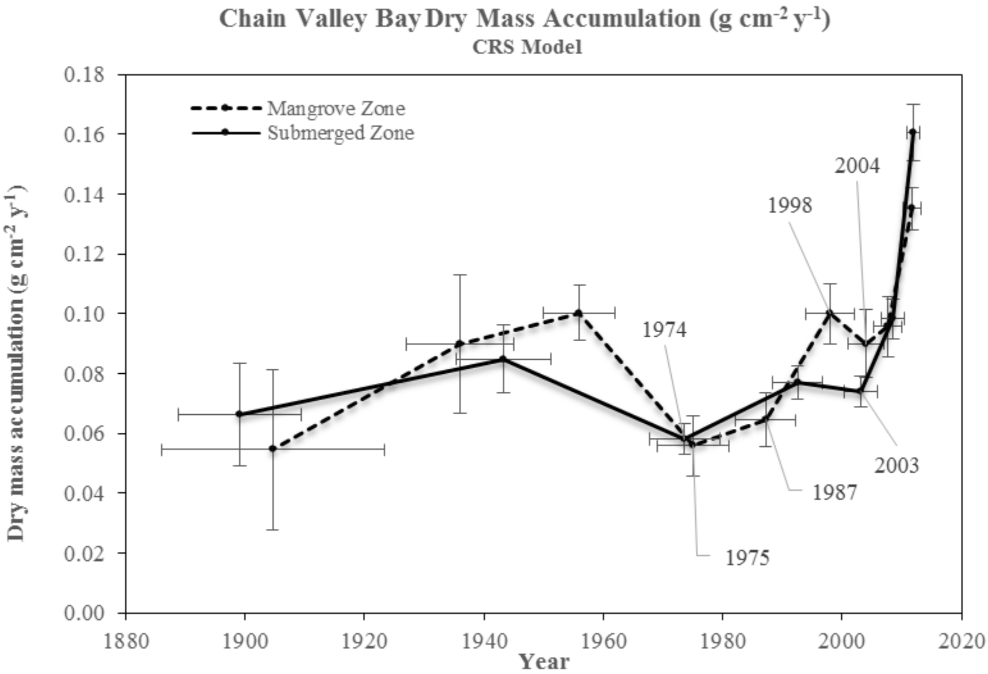


Figure 5-16 Mass Accumulation (g cm^{-2} y^{-1}) (±SD) at Chain Valley Bay within mangrove and submerged areas calculated use ^{210}Pb radiometric isotopes.

1.22 **Sediment Characteristics and Carbon Storage**

Bulk Density, % Moisture, and sediment composition analysis was undertaken to help characterise the wetland stratigraphy and upper organic layer. These results are represented in Figure 5-18 to Figure 5-24.

Sediment characteristics and carbon storage in each vegetation zone changes with depth.

Cores A1 and A2 obtained from submerged areas have dark organic material consisting of mangrove roots (Figure 5-18 and Figure 5-17). Gravel was more abundant at 15cm in core 1A than core 2A, although some gravel was found in the upper 15 cm mixed with sand. From 15 cm- 75 cm the cores are filled with grey sand indicating the fluvial delta. Following the sand area the cores transition to grey clay to the bottom of the core and is likely part of the central mud basin. The core located in transect 1 also had some yellow clay at 75 cm and some shell material occurs in both cores around 75 cm. Bulk density starts at 0.6 g and decreases to approximately 0.2 g at 15 cm and gradually decreases down the core and represents the reduction in organic matter. In the upper 15 cm sediments core 2A is composed of 70% silt and 20% sand and some clay and core 1A is composed of 60% silts and 35% sand. A switch from mainly silt to sand occurs from 25 – 95 cm. Core 2A has silt dominating from 105 to 115 cm and switches to mainly sand briefly at 125 cm and then continues as predominantly silt. Core 1A also has this switch within 85 – 105cm down the core.

1A

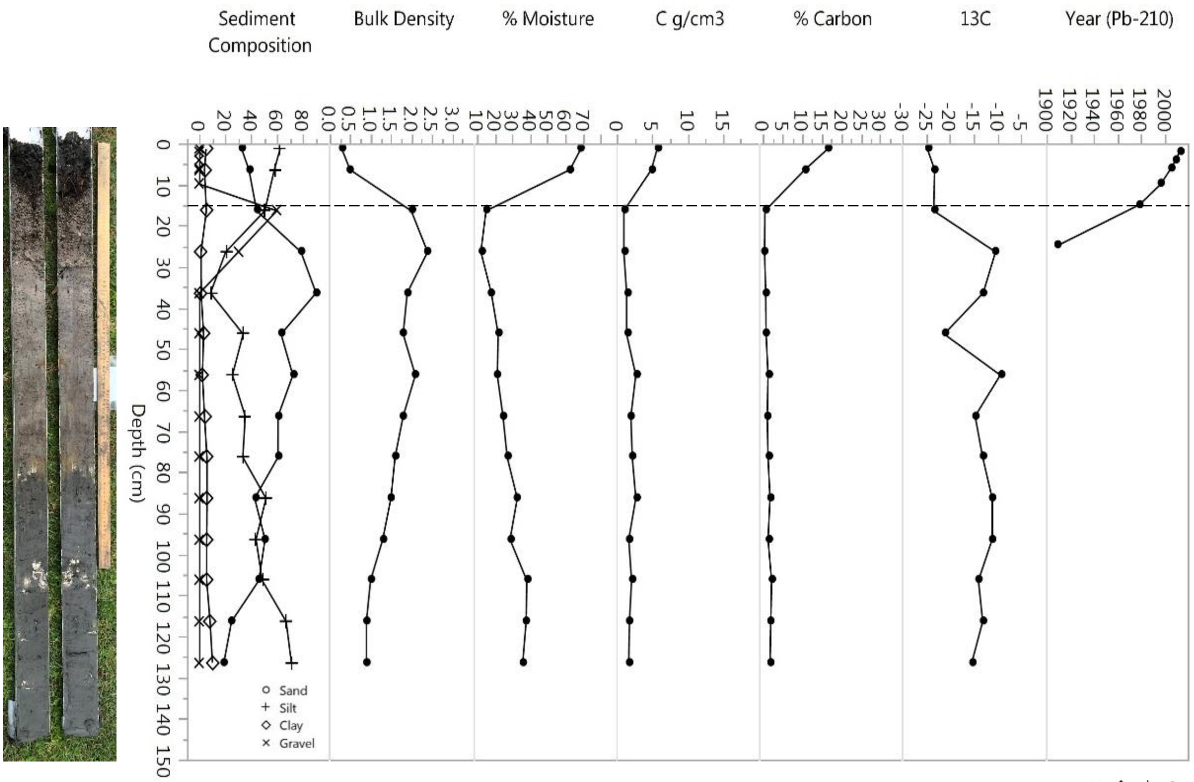


Figure 5-17 Submerged core 1A located in the submerged section of the wetland located at the front.

2A

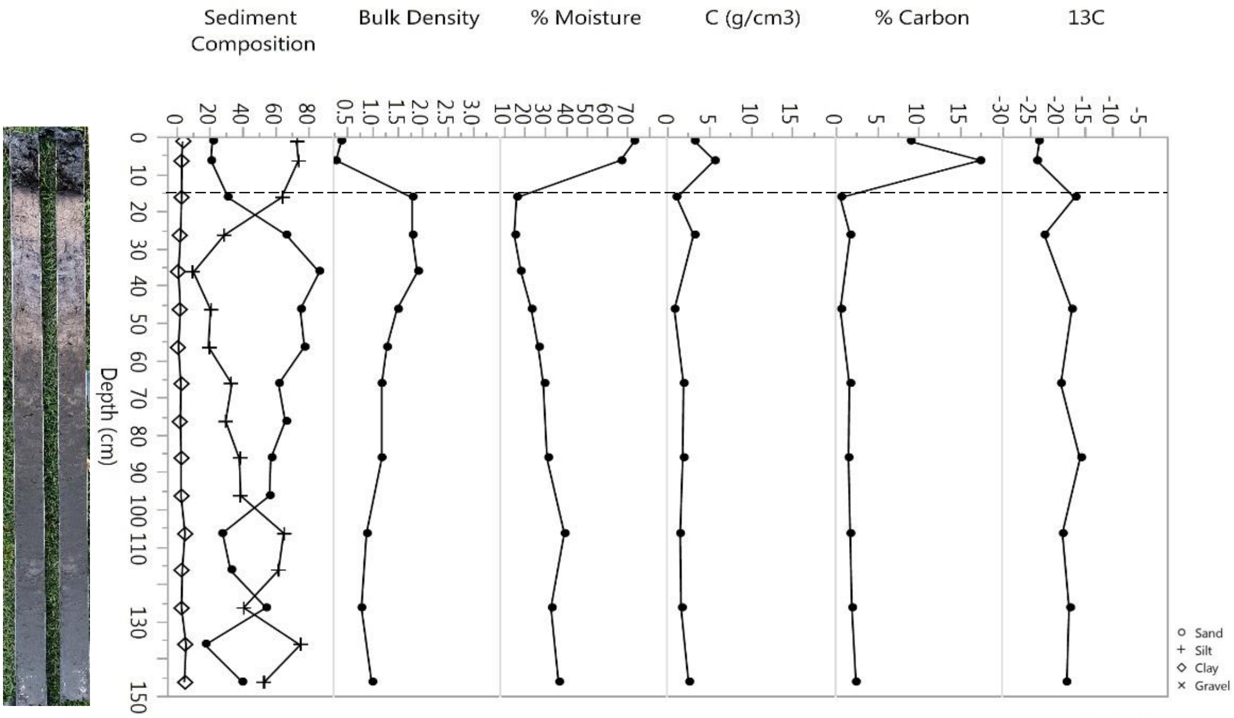


Figure 5-18 Submerged core 2A located in the submerged section of the wetland located at the front.

Cores located within the mangrove area have dark organic material consisting of mangrove roots and soil that transitions at 35 cm down the core into grey sand with some small rocks . At 75 cm sticky yellow orange and grey clay appear and at 85 cm a little shell material was found. Below 85 cm the shell material increases and the mud is dark grey. It appears the fluvial delta appears between 35 cm and 75 cm and the central mud basin continues to the bottom of the core. Bulk density starts at 0.2 g cm^{-3} and increases to 1.5 g cm^{-3} at the transition point from organic material to sand. Silt dominate the organic section and the marine lower section in the core and sand dominates the fluvial delta middle section of the core. Lots of gravel was found at 65 cm within the mangrove core obtained from transect 1, and may correspond to the gravel layer at 15 cm within the submerged core in transect one. Clay slightly increases down core in 2B.

1B

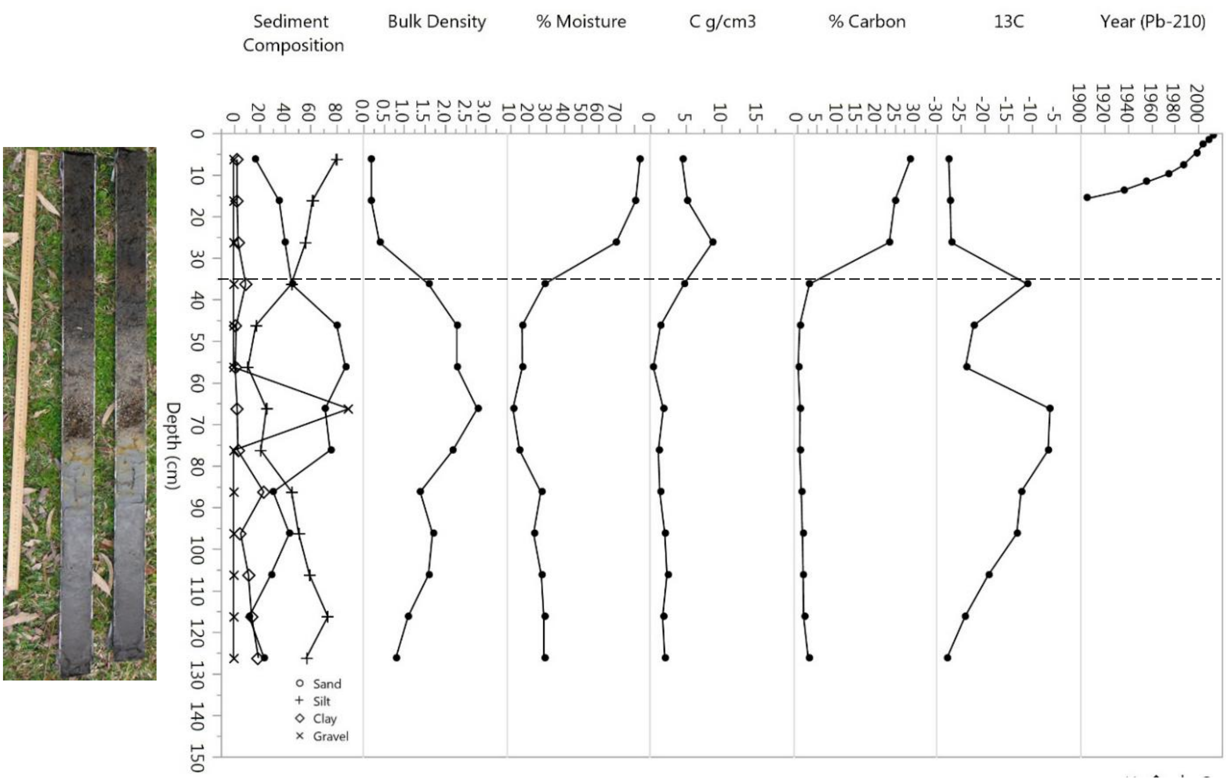


Figure 5-19 Mangrove core 1B located in the mangrove section of the wetland on transect 1.

2B

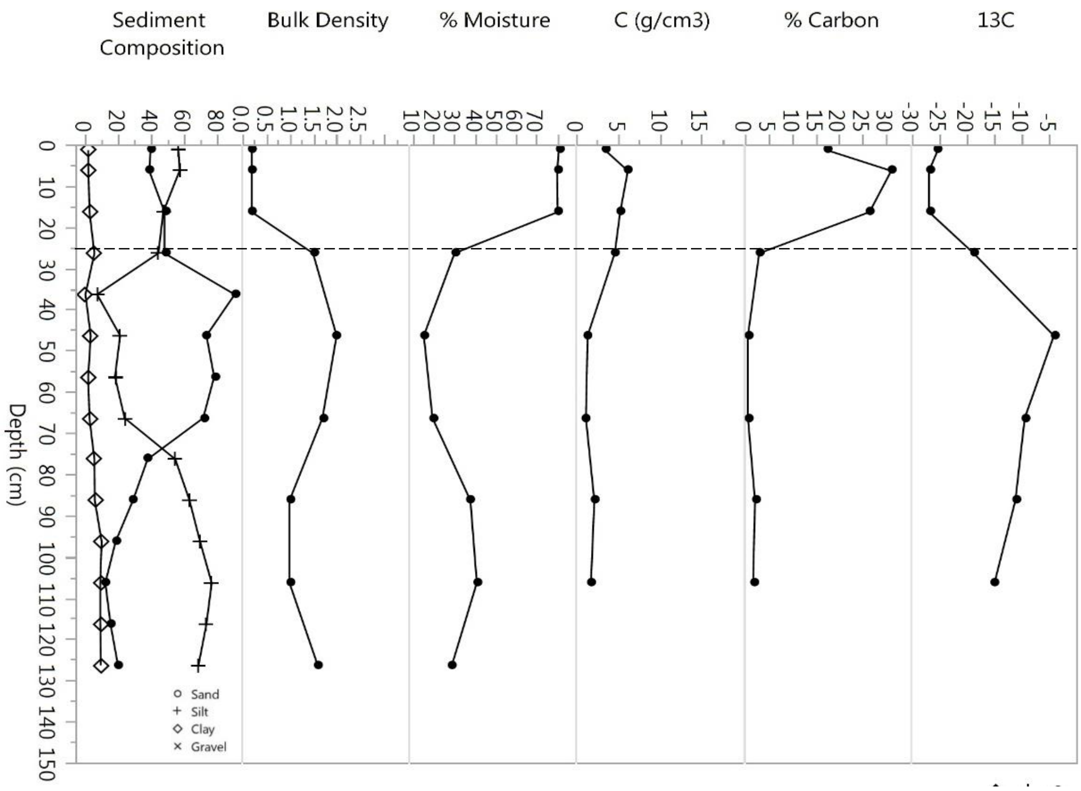


Figure 5-20 Mangrove core 2B located in the mangrove section of the wetland on transect 2.

Within the saltmarsh area cores have dark organic material mixed with fine sediments from 0-25 cm down the core (Figure 5-21 and Figure 5-22). Grey fluvial delta sediments occur from 25 – 65 cm and marine central mud basin sediments occur from 65cm down the core and are characterised as dark grey and stodgy. Some shell material was found at 65 cm within the saltmarsh core 2C. Bulk density increases from approximately 0.3 to 2.0 g cm^{-3} at 75 cm within the core from transect 1 and 45cm in the core from transect 2. A high amount of gravel is located at 65cm within core 1C and could likely correspond to the gravel layers in the other transect 1 cores. In 1C sand and silt dominate the upper 25 cm of the core. Sand, silt and clay fluctuate between 45 and 75 cm and then are dominated by silt within the lower core.

1C

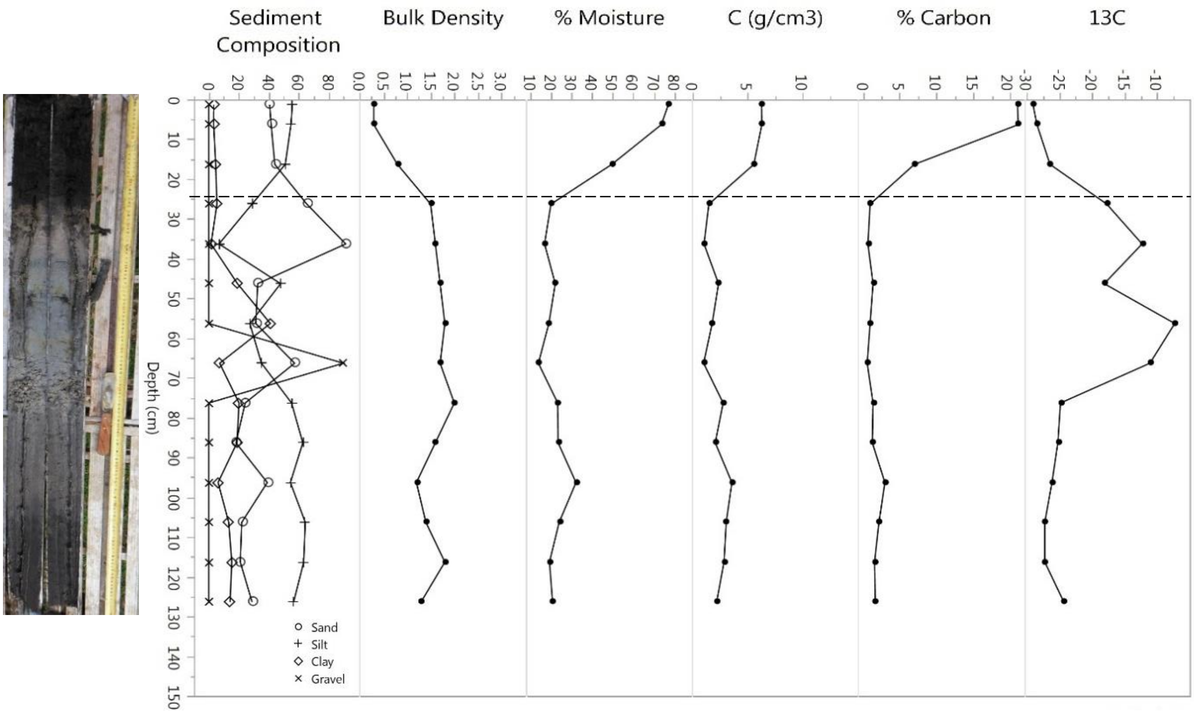


Figure 5-21 Saltmarsh core 1C located in the salt marsh area of the wetland within transect 1.

2C

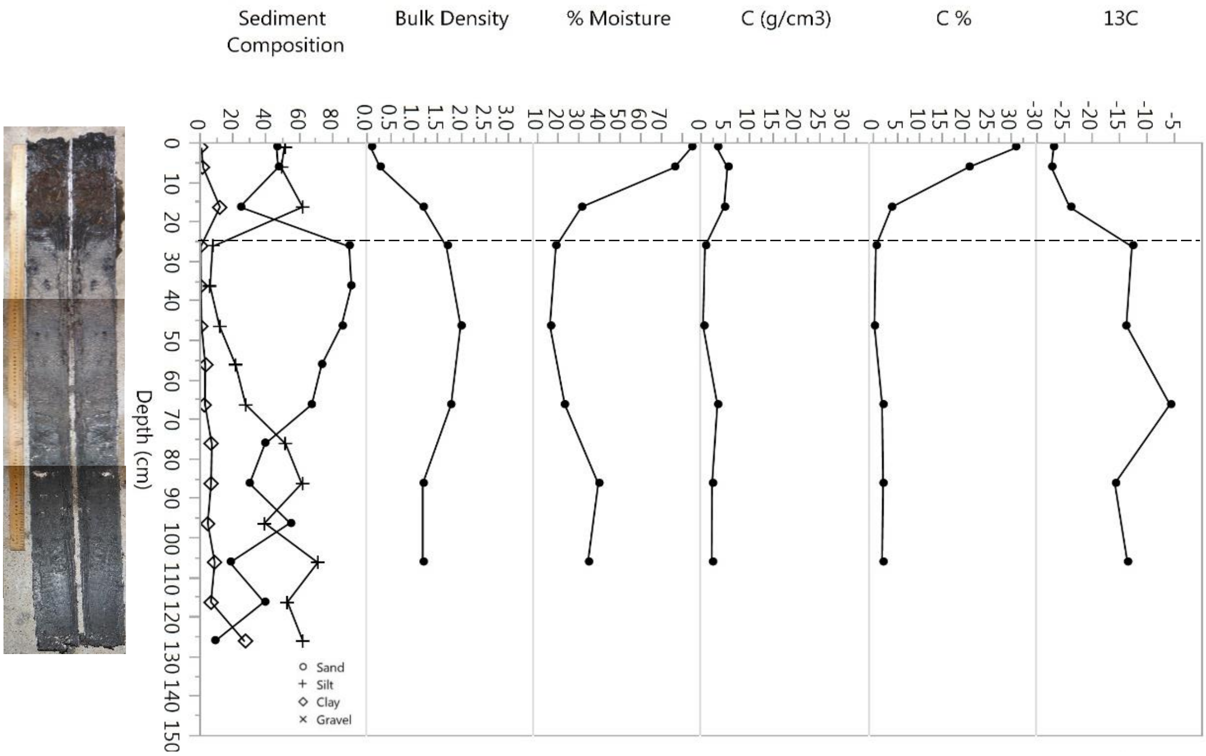


Figure 5-22 Saltmarsh core 2C located in the salt marsh area of the wetland within transect 2.

Dark organic material occurs from 0 – 35 cm in core 1D, from 0-25 cm in core 2D and E all located within the mixed forest zone (Figure 5-23, Figure 5-24 and Figure 5-25). Grey sediments from the fluvial basin occur after the organic layer until 65 cm in cores 2D and 1D but appears at 45 cm in core 1D. The sediments after the sandy material consist of dark grey sticky mud from the central mud basin. Yellow clay appears from 35 to 85 cm within core E, and 45-65 cm within core 1D. Bulk density increases down the core within the organic material from 0.2 to 1.7 g cm^{-3}. Bulk density within core 2D increases to 2.5 g cm^{-3} at 75 cm and decreases there after. Cores 1D and E retain bulk density values around 1.5 g cm^{-3}. Core 1D is dominated by silt sediments within the organic upper core and transition to sand dominated where the fluvial sourced sediments reside. Silt increases from 65 cm and clay content also increases. Core 2D is silt dominated with some sand in the upper organic material section of the core and transitions to sand and then silt. Clay increase at 75 cm and then increases again at 115 cm within core 2D. Within core E silt dominates the upper organic section of the core and transitions to sand dominated from 25 cm to 40 cm and then sand and clay fluctuate inversely down the core until it is mostly clay and silt dominated from 115 cm.

1D

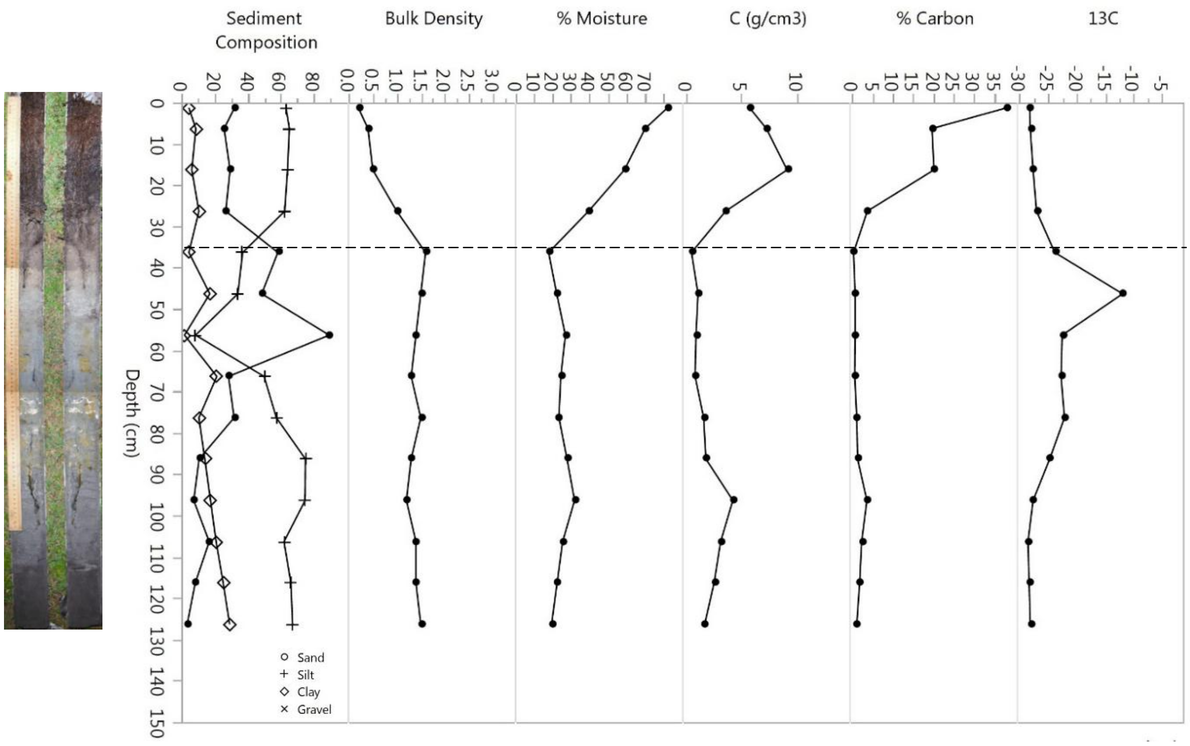


Figure 5-23 Core 1D located in the mixed forest zone of the wetland in transect 1.

2D

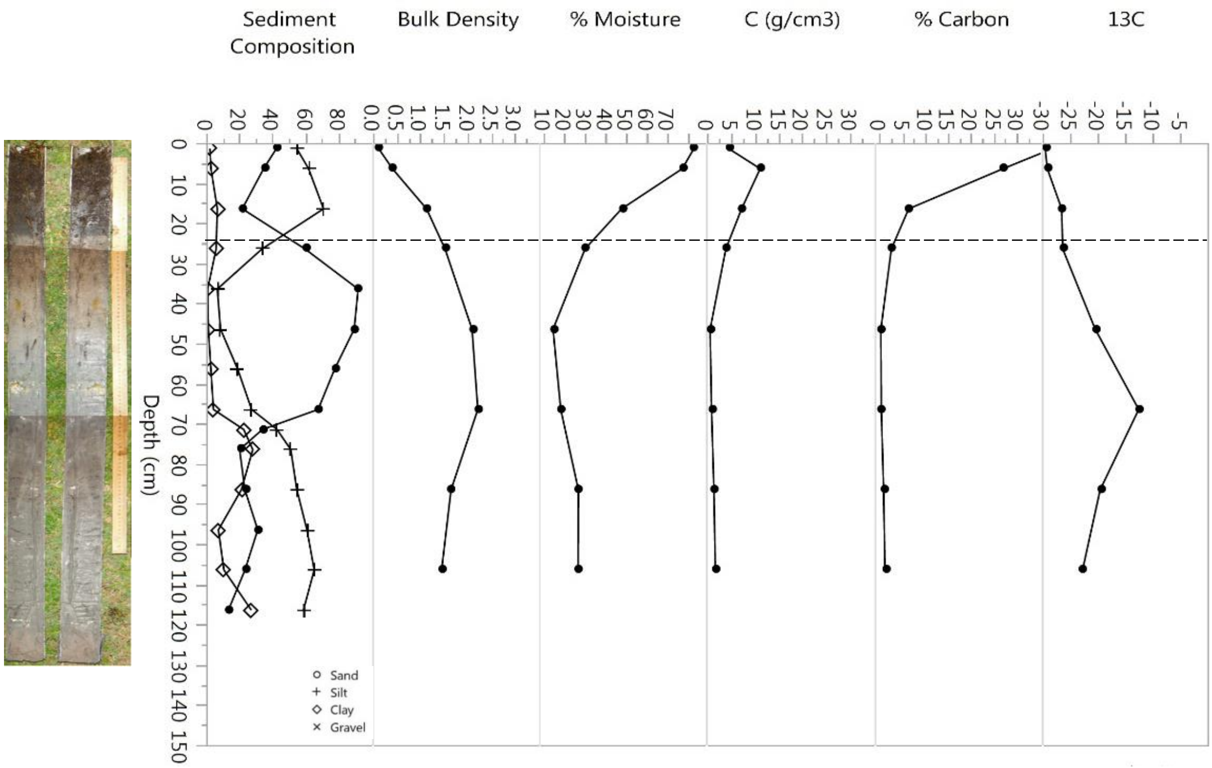


Figure 5-24 Core 2D located in the mixed forest zone of the wetland in transect 2.

E

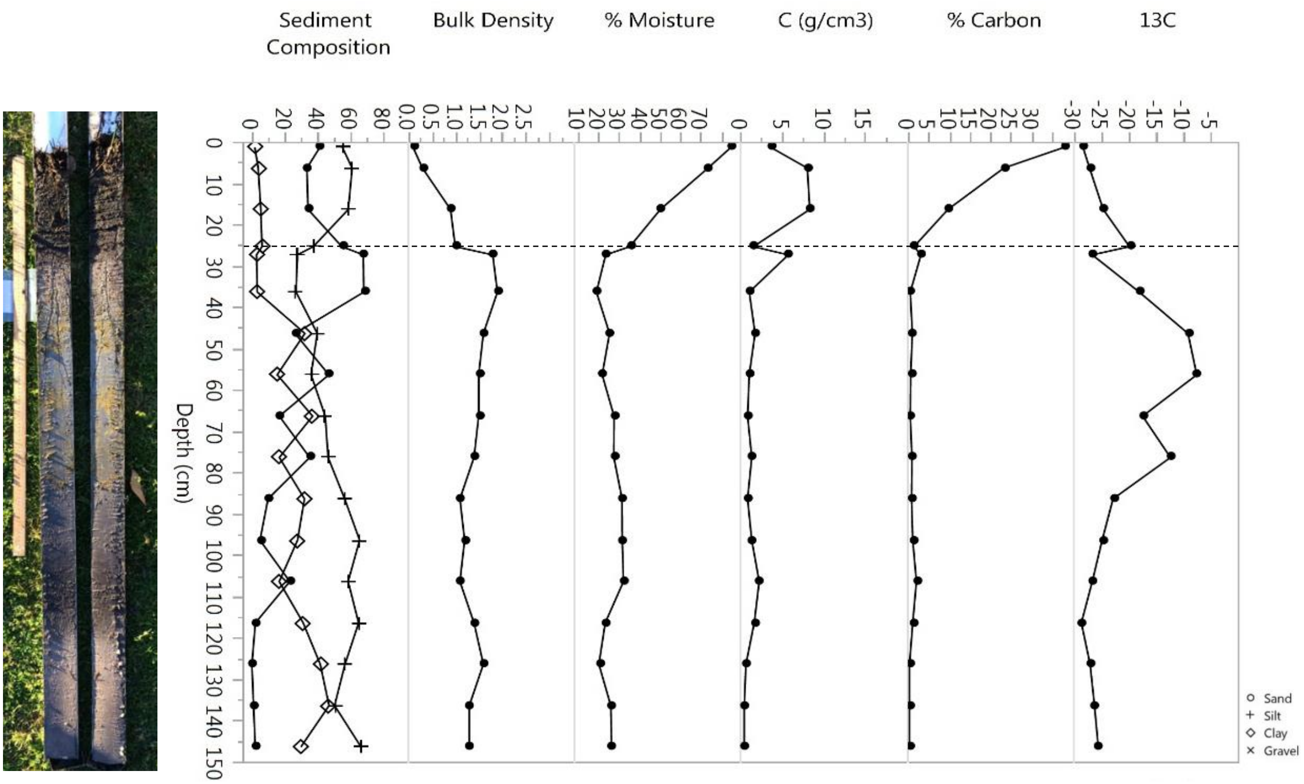


Figure 5-25 Core E located in the mixed forest zone of the wetland between transects 1 and 2 and is the furthest landward core.

The upper dark organic section of the cores are predominantly composed of silt particles and transitions to fluvial delta sediments dominated by sand and then transitions to marine central mud basin sediments to the bottom of the core. The submerged cores have less organic material within their upper core and it has perhaps been removed during the rapid subsidence. Bulk density gradually moves from small values of 0.2-0.3 g cm^3 from the surface of cores to values of 1.5-2.0 g cm^3 at the transition to fluvial delta and central mud basin sediments. This pattern is seen in all cores but at different depths and is indicated by a dotted line on the figures above. Cores from submerged areas have the transition to fluvial sediments at 15 cm, mangroves cores from 25 to 35 cm, saltmarsh cores at 25 cm and mixed forest cores from 25 to 35 cm. Moving down the core the bulk density fluctuates between values of 1.00 and 3.00 g cm^3. The percent moisture moves from a maximum of 80% to 20% at the transition to marine sediments and indicates the moisture held by organic material.

1.22.1 Carbon Sources

Carbon content and stable isotope analysis was undertaken at Chain Valley Bay to estimate the carbon sequestered and the carbon sources within different zones of the wetland and the changes due to inundation. In all cores there is a transition from one carbon sources to another.

Carbon isotope signatures divided into four groups; marine carbonates, terrestrial C3, terrestrial C4 and terrestrial/marine vegetation which are terrestrial vegetation but source carbon from the water column. Common species present within the Chain Valley Bay wetland were recorded as likely carbon sources. The possible signatures are used as a reference for carbon isotopic results obtained from Chain Valley Bay (Table 4-2).

Submerged core 1A transitions from *Avivennia marina* values of -25‰ to marine *Zonstera Capricornia* of values of -11‰ between 15 and 25 cm. The upper terrestrial C3 mangrove vegetation has likely been sourced from dead mangrove vegetation that is remaining since inundation. The Submerged core 2A transitions from mangrove vegetation to a carbon isotopic value of -16‰ which could indicate *Sporobolus virginicus* carbon sources. This could suggest the area was populated by saltmarsh vegetation and following submergence mangrove material, either dead or from nearby plants, became the main source of carbon. As both cores have mangrove material as sources following inundation it could reflect the obvious remaining material from the tree that died from inundation and also the new material they produced after recolonising the wetland soon after inundation. Isotopic values at lower depths within the cores appear to be skewed by the presence of *Andara trapezia* carbonate material.

In the mangrove core 1B the carbon isotopic value starts at -28‰ (*Avicennia marina*) and transitions to -11‰ (*Zostera Capricornia*) marine C4 vegetation. This is an obvious transition from marine vegetation to terrestrial vegetation up the core and would indicate the transition from the fluvial delta. The mangrove core 2B has a transition from isotopic values of -25‰ indicating *Avicennia marina* to -18‰ isotopic values indicating *Sporobolus virginicus*. The inclusion of saltmarsh vegetation *Sporobolus* would indicate the area was saltmarsh and has been taken over by mangrove following inundation. Below the saltmarsh section the isotopic values approach zero indicating the likely presence of *Anadara trapezia* carbonate material from the fluvial delta and central mud basin.

The saltmarsh core 1C transitions from -30‰ to -24‰ $\delta^{13}C$ values at 15 cm indicating a transition from mixed forest vegetation to mangrove. Down the core the mangrove vegetation becomes saltmarsh *Sporobolus virginicus* at 25 cm with isotopic value of -17 and then at 35cm has values corresponding to *Zostera capricornia*. The transition of carbon sources suggests the area was once fluvial delta and has been colonised by saltmarsh and then mangrove. Following inundation carbon has been sourced from *Casurina* and *Melaleuca* perhaps from dead vegetation falling or settling into the area. The area the core was collected is swampy with permanent water approximately 40 cm deep and dead leaves and vegetation could easily settle within the water. Saltmarsh core 2C has carbon isotopic values of -27‰ corresponding to saltmarsh vegetation *Juncas kraussii* at the top of the core. This transitions to mangrove sources at 15 cm and then marine seagrass *Zostera* sources at 25 cm. The succession indicates the area was fluvial delta and has been colonised by mangrove and then saltmarsh following the inundation event.

In the mixed forest 1D carbon values of -30‰ and -28‰ corresponding to *Casuarina* and *Melaleuca* vegetation transition to mangrove isotopic values at 35 cm and then marine seagrass values at 45 cm. Core 2D shows a similar trend but transitions to mangrove at 15 cm. Core E located furthest south also has a transition to mangrove vegetation sources at 15 cm but transitions to saltmarsh vegetation *Sporobolus virginicus* at 35cm and marine carbon sources at 45 cm. There is a mangrove signature at 28 cm but this is thought to be a product of sediment mixing during extraction.

1.22.2 Carbon Dynamics

In each core there was a noticeable difference between the sediment composition, bulk density and amount of carbon between the terrestrial sourced carbon and the marine sourced carbon. Most carbon is within the upper core above the transition zones identified in Table 5-5 below.

Table 5-5 Transition point between changes in bulk density, % carbon, isotopic signatures and sediment characteristics.

Core	Transition Zone (cm)
1A	15
2A	15
1B	35
2B	25
1C	25
2C	25
1D	35
2D	25
E	25

The percent carbon differs for each vegetation zone which suggests some areas of the wetland have a better capacity to store below ground carbon. Mixed forest cores which suffered the least amount of inundation had a high value carbon of37% at the top of the cores. Mangrove cores had maximum values of 30%, saltmarsh had values ranging from 32% to 20%, and submerged areas only had maximum value of 12 – 17% carbon. At the transition to marine sediments in all cores the % carbon eventually reduces to 0%. The amount of carbon stored in each core above the delineated transition zone was calculated using bulk density and % carbon values. Bulk density and % carbon values have an inverse relationship the occurrence of organic material. The mixed forest zone has the most carbon followed by mangrove, saltmarsh and submerged areas. Vegetation mapping of the wetland from 2010 to 2014 show a reduction in saltmarsh due to mixed forest and mangrove expansion. This expansion may be an attempt by the wetland to sequester more carbon as saltmarsh within the wetland do not appear to store carbon as effectively (Figure 5-26). Below the transition point recalcitrant carbon within the central mud basin sediments remain.

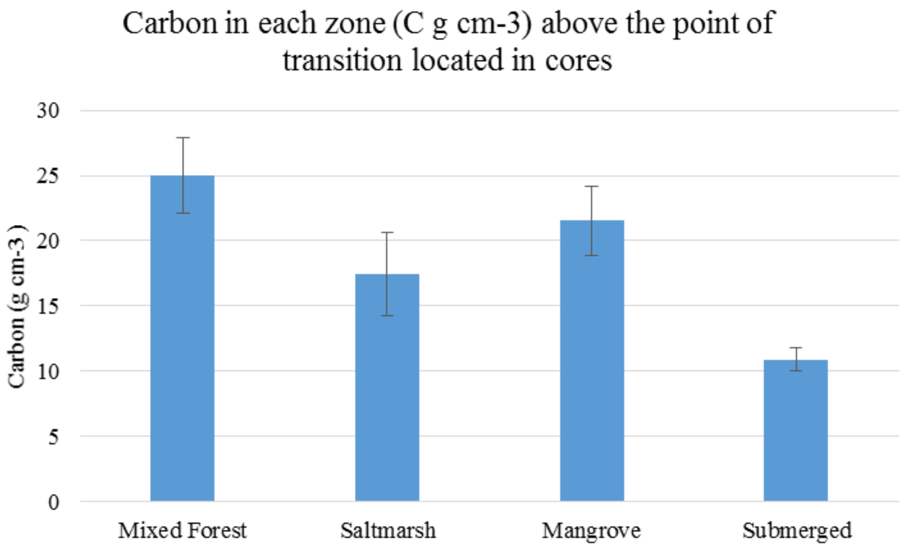


Figure 5-26 Carbon values (±SD) in each vegetation zone of the Chain Valley Bay wetland determined using bulk density and % carbon information. Mixed forest and mangrove appear to be storing the most carbon.

1.23 **Chapter Summary**

In summary vegetation transitions is an indicator of impacts due to inundation. A zone of impact and rapid death in vegetation is seen after inundation occurs but mangrove recolonizes. The current mangrove expansion is moving up to higher elevations colonised by saltmarsh. Bathymetry data shows a remnant wetland exists and combined with DEM data a maximum of -0.924 m elevation decrease has thought to have occurred in the mixed forest area.

Terrestrial carbon sources are located in the upper sections of the cores and transitions to marine sources. The terrestrial upper section of the cores have higher % carbon, higher % moisture, higher bulk density and higher grain size than those found in the marine section of the core at the transition point.

Mass accumulation in both the mangrove core and the submerged core increased rapidly since inundation of the wetland started to occur and indicates mixing of mineral based sediments with silt. Current rates of accretion in the submerged core indicate terrestrial organic carbon has been rapidly accreting in submerged zones and at a constant rate in mangrove areas since inundation. The mangrove area that was not submerged has had steady accretion and therefore a steady rate of carbon sequestration of mangrove sourced material since the mine collapse. The submerged area has had rapid accretion and all carbon in the upper terrestrial section of the core has been stored after inundation. Carbon sequestration has increased from 300 g C m^{-2} yr^{-1} to 627.3 g C m^{-2} yr^{-1} and appears to indicate the wetlands attempt to keep up with water level rise. Isotopic results have revealed a transition from vegetation from marine sources to terrestrial sources. Terrestrial vegetation is the dominant vegetation within the upper depths in cores and is indicated by a transition point. Nearby mangrove vegetation is the dominant source of carbon in the submerged zone. The amount of carbon in each vegetation zone reflects the capability of mixed forest and mangrove to store more carbon than saltmarsh areas.

6. DISCUSSION

The Chain Valley Bay wetland located at the southern end of Lake Macquarie on the NSW Central Coast has suffered rapid inundation since 1986 when a long wall mine collapsed due to pillar removal (Yee et al., 1991). This event has created the opportunity to use it as surrogate for rapid sea-level rise and analyse the changes within a wetland. These ecosystems help mitigate climate change by sequestering and storing significant amounts of carbon and are known as coastal blue carbon sinks (McLeod et al., 2011). Blue carbon sinks account for approximately half of global carbon burial in marine sediments (Nellemann et al., 2009). Losses of carbon stored within wetlands has been related to sea-level rise; accumulation rate; subsidence; storm events; rate of wetland loss and coastal restoration (DeLaune and White, 2012; Kirwan and Mudd, 2012). The effect of rapid sea level rise on wetland vegetation sequestration ability and the fate of carbon is little understood (Choi and Wang 2001; Mcleod et al., 2011).

1.24 Vegetation characteristics

There is an obvious change in vegetation following rapid inundation and a successive die back and return of vegetation. Following inundation due to subsidence, the front of the wetland suffered extensive vegetation death likely due to inundation reaching a critical rate and drowning vegetation. The vegetation death continued to move south-east through the wetland over time where the effects of inundation were less noticeable due to higher elevation. Mangrove species *Avicennia marina* colonised previously dead zones after approximately 16 years. Following the return of mangrove, saltmarsh areas started to also colonise but mangrove encroachment landward has consequently caused saltmarsh decline. This trend has occurred elsewhere in coastal wetlands located on South-East Australia and the cause has been related to sea level rise (Rogers et al., 2006; Saintilan and Williams, 1999; Oliver et al., 2012). Mixed forest zones started to return together with mangrove and saltmarsh but as with mangrove encroachment, mixed forest has begun colonising in saltmarsh areas. If this is to continue the saltmarsh areas could encounter reduced species variability with sea-level rise (Thomas et al., 2012; Saintilan and Williams, 1999). Chmura (2013) suggests vegetation acting as a carbon sink may survive if allowed to migrate inland uninhibited by barriers such as high slope or development.

Implications for rapid sea-level rise suggests wetland vegetation like that seen at Chain Valley Bay located in a wave-dominated barrier estuary can recover at higher elevations after inundation occurs. The degree of carbon associated with mangroves compared to saltmarshes is more within mangroves of the Chain Valley Bay wetlands. Mangrove vegetation increases below ground carbon store, elevating the wetland surface by increasing the soil volume with roots. Within the active carbon storage layer in the upper stratigraphy, the mangroves of Chain Valley Bay store 22 g cm^{-3} and saltmarshes store 17 g cm^{-3} of carbon. The mixed forest area stores the most carbon within the entire wetland with 25 g cm^{-3}. The mixed forest and mangrove encroachment into saltmarsh areas is likely an indication of the wetland attempting to accrete to catch up with water level and as a result is sequestering carbon more efficiently and could be an indicator the wetland is still adjusting to the water level rise (Kirwin and Mudd, 2012). The growth in high carbon sequestration vegetation like the mangrove and mixed forest areas will likely provide benefits to our future climate and the removal of carbon from the atmosphere and oceans.

1.25 **Wetland morphology**

Elevation within the wetland increases from the shore to the landward side successively through vegetation zones. Elevation of vegetation zones through time show mangrove and saltmarsh vegetation have similar elevations but mixed forest appears at higher elevations at the back of the wetland. RTK-GPS derived elevation points were combined with DEM points to give an approximate elevation for each vegetation zone in the wetland. Mangrove vegetation had 0.112 m elevation, saltmarsh 0.153 m elevation and mixed forest 0.674 m elevation.

Using elevation level characteristic of mixed forest and the bathymetry of the remnant of the wetland obtained in 2011, it was estimated -0.924 m current subsidence has occurred within the mixed forest area at the front of the wetland. In comparison, a value from 1991 of -0.85 m subsidence is reported and it appears subsidence has continued to occur from 1991 to 2011. Bathymetry mapping reveals evidence of the remnant wetland that has undergone inundation due to the mine collapse.

1.26 **Carbon Accretion**

As the ocean heats and CO_2 is absorbed its ability to buffer atmospheric change reduces, causing impacts to ecosystems. The ability of the wetland to continue to sequester carbon after inundation is important, as freeing carbon stored below ground causes CO_2 to be released and dissolve into sea water (Nellemann et al., 2009).

Accretion and mass accumulation within mangrove areas in 2014 at Chain Valley Bay suggest following inundation and death of vegetation, colonising mangroves are able to keep pace and continue to accrete at a constant rate. An increase in mass accumulation in this stable accretion zone is likely due to an enrichment of mineral based sediments immediately following submergence. Wetlands that have suffered inundation and do not have adequate sediment supply can lose wetland area (Mudd et al., 2009; Woodroffe et al., 2014). The rapid period of colonisation by mangroves after mass vegetation death in higher elevation zones indicates they are relatively adaptable to inundation and can survive by landward extension when there are no barriers (Chmura, 2013).

Areas that have endured permanent inundation due to subsidence, recent accretion indicates sediment supply is sufficient to sequester carbon. Mass accumulation indicates rapid recent organic and mineral based deposition in submerged areas with an increase of 0.09 g cm^{-2} y^{-1} from before inundation to 2014. The results suggest no net loss has occurred and the wetland is likely still adjusting to the inundation level. The amount of carbon stored in the upper organic layer in submerged areas is much less than those in higher elevations and ^{210}Pb dating indicates all below ground carbon located in the upper 16 cm has been deposited following inundation. Although the amount of carbon is less than the mangrove area, the rate of accumulation is greater, suggesting carbon sequestration could have increased as well. The rate of carbon sequestration before inundation in the submerged area was 300 g C m^{-2} y^{-1} and the rate in the mangrove area was 56 g C m^{-2} y^{-1}. Following the occurrence of inundation the mangrove carbon sequestration only increased to 68 g C m^{-2} y^{-1} but the submerged area had a massive increase in the sequestration of carbon to 627.3 g C m^{-2} y^{-1}. The increase in the submerged area is more than double what it was previously and could be indicating the wetlands attempt to keep up with water level rise. DeLaune and White (2012) found high energy environments that encounter large hurricane events like those found in coastal Louisiana, cause marshes to become net carbon emitters following sea level rise. Kirwan and Mudd's (2012) study also predicted marshes would become net carbon emitters following submergence with their study into protected micotidal-mesotidal North American marshes dominated by *Spartina alterniflora*. They believe with sea level rise burial rates would decline after an initial increase and the marshes would not be able to recover. The Chain Valley Bay wetland, which is located on a fluvial delta entering a central mud basin and where hydrodynamic conditions are low energy, has sequestered carbon in the submerged area at a rate on average of 10 mm y^{-1} since submergence in 1986. This is 7 mm y^{-1} greater than the rate prior to submergence and indicates that following a short period of erosion, the site has a greater capacity to sequester carbon than prior to submergence and is in fact not a net emitter of carbon to the atmosphere. The Chain Valley Bay site is typical of South-East Australian estuaries that have low energy micro-tides with a temperate climate, low sediment supply and small stream discharge. The findings may suggest wetlands located within this region would not become net carbon emitters following sea level rise and would be able to continue sequestering carbon.

1.27 Changes in carbon sources

The $\delta^{13}C$ values within each core transitions from marine to terrestrial in the upper section of cores where there is a high % carbon content. A transition point in each core was delineated based on a shift within sediment composition, bulk density, % moisture and % carbon. Carbon isotopic values were matched with vegetation carbon signatures and each vegetation was separated into different photosynthetic-type plants C3 and C4.

Vegetation above the transition zone is C4 and corresponds to dominant vegetation within the wetland at which the core was extracted. Within the mixed vegetation zone current C4 vegetation *Casuarina glauca* and *Melaleuca quinquenervia* correspond with the $\delta^{13}C$ value at the top of the cores but at the transition point between 25-35 cm moves to mangrove. Within the mixed vegetation core E located the furthest south-east it transitions to *Sporobolus virginicus* C4 saltmarsh vegetation after mangrove and could suggest mangrove vegetation has replaced saltmarsh. All mixed forest cores suggest mangrove vegetation has moved out of this area to allow for mixed forest colonisation perhaps as a result in sea level fluctuations.

The mangrove zone had a transition from mangrove vegetation at the top of the core to C3 marine vegetation sources which gather carbon from the water column rather than atmospheric CO_2. The saltmarsh cores both transition to C3 marine vegetation likely sourced from *Zostera Capricornia* with a $\delta^{13}C$ value of -10.8 to -11.7 from terrestrial C4 vegetation. The saltmarsh core 2C moved from saltmarsh sources to mangrove and then marine sources suggesting saltmarsh has colonised a previously mangrove zone since inundation. The saltmarsh core 1C transitions from mixed forest to mangrove and then to saltmarsh *Sporobolus virginicus* values followed by marine. This different transition could suggest this area was saltmarsh and was replaced by mangrove and following mass vegetation death, dead *Casuarina* and *Melaleuca* organic material has collected in the depression.

The submerged zone is currently not vegetated but does have organic material corresponding to C4 mangrove $\delta^{13}C$ values within the top 10 to 15cm which has likely been sourced from drowned mangrove vegetation. The 1A submerged core indicates a transition to seagrass like the majority of locations but core 2A indicates a transitions similar to the $\delta^{13}C$ value of C4 saltmarsh vegetation

Sporobolus virginicus. This shift could suggest saltmarsh was occurring sporadically in this section before inundation occurred and is seen in vegetation zone mapping.

The eventual transition of all cores to marine based C3 vegetation could suggest past sea-level rise and inundation. It could also be part of the marine central mud basing and the fluvial delta that have since undergone, and still is undergoing, sedimentation in accordance with its youthful barrier estuary status (Roy et al., 2001).

Carbon stored within the upper core differed in each vegetation zone. It was found mangrove had the most terrestrial based carbon stored in the upper stratigraphy followed by mixed forest, saltmarsh and the submerged area. The submerged area and the mangrove area have been accumulating carbon rapidly since inundation occurred which is indicated by mass accumulation values at the site.

1.28 **Implications of sea-level rise**

With increasing sea level rise it is possible inundated areas will suffer loss of upper soil organic carbon and become carbon sources rather than sinks (Choi and Wang, 2001; McLeod et al., 2011). Vegetation zonation movement appears to be driven by the degree of inundation into a wetland and the ability of vegetation to sequester carbon. Carbon sequestration within the inundated wetland increased; likely due to the availability of sediments and good hydrodynamic conditions. It appears the wetland is trying to keep up with water level increases and as a result is increasing sequestration. Accretion of sediments within the mangrove area didn't change noticeably although mass accumulation increased; likely due to mineral based sediment additions. Sources of carbon stored within the wetland is terrestrial but was previously marine sourced and could suggest past sea-level fluctuations and the movement of terrestrial vegetation into an estuary. The upper layer of the submerged cores has recent accumulation showing it has begun to sequester carbon rapidly. The source of carbon within the submerged area is mangrove material which was revealed using carbon isotopic analysis and could have been sourced from drowned mangrove vegetation within the surrounding area. DeLaune and White (2012) and Kirwan and Mudd (2012) research suggests coastal environments would become net carbon emitters following sea level rise. This study suggests following rapid sea level rise wetlands like Chain Valley Bay located on the south-east coast of Australia would not become net carbon emitters.

1.29 **Limitations**

The characterisation of morphodynamics of the Chain Valley Bay wetland was inhibited by the inability to obtain older bathymetry data to allow for the comparison between sediment removal and additions. Carbon isotopic analysis below the obvious transition from terrestrial to marine sources could not be used due to the remaining presence of carbonate material and a longer history of sequestration and carbon sources could not be constructed. More acid washing of sediments to remove remaining carbonate material is to be conducted following submission. Nitrogen isotope analysis was also undertaken but results were received too late to be included. The addition of above-ground biomass data to the current results of carbon sequestration in Chain Valley Bay would have been added to determine the total amount of carbon lost to inundation but time constraints limited this. Allometric equations using non-invasive methods would have been used.

1.30 **Chapter Summary**

Coastal environments provide ecosystem and carbon storage benefits. Wetlands like Chain Valley Bay, Lake Macquarie, NSW Australia are known as blue carbon sinks and sequester large amounts of carbon. The effects on the storage potential within these systems following sea level is not well known. This study found following rapid inundation large amounts of vegetation died and was later replaced with mangrove and saltmarsh vegetation. Accretion increased in submerged areas following inundation and the sequestration of carbon doubled. Mass accumulation increased dramatically in both submerged and mangrove areas and is likely due to mineral based sediment increase. Carbon sources within the submerged area indicate the area has been storing mangrove material following inundation and is likely from remaining dead mangrove material and material sourced from nearby vegetation that has colonised the front of the wetland. Increased sequestration within the wetland has likely occurred as a results of the wetland attempting to keep up with water level rise. The study suggests following sea-level rise the wetland is not a net carbon emitter.

7. CONCLUSIONS AND RECOMMENDATIONS

1.31 Conclusions

Blue carbon sinks are beginning to be recognised for their ability to sequester large amounts of carbon from the atmosphere and oceans which could help mitigate climate change (Nellemann et al., 2009; McLeod et al., 2011; Chmura, 2013; Duarte et al., 2010; Duarte et al., 2005; Pendleton et al., 2012). Carbon sequestered in coastal soils can be extensive and can remain trapped for long periods of time (Duarte et al., 2005). The possible impacts due to sea-level rise have not been extensively recognised and there is a gap in our understanding of the fate of buried carbon when wetlands become submerged or eroded (McLeod et al., 2011). Some studies indicate that sea level rise lead to wetlands becoming net carbon emitters (DeLaune and White, 2012; Kirwan and Mudd, 2012) as they become submerged or eroded. This study used mine subsidence as a surrogate for rapid sea level rise to determine whether this was indeed the case for a wetland located within a low energy environment.

The Chain Valley Bay wetland experienced rapid inundation due to mining subsidence resultant of partial pillar extraction in a long wall mine under the wetland in 1986. Subsidence of -0.846 m was recorded in June 1991 near the wetland (Yee et al., 1991).
Vegetation spatial mapping indicate the sudden death and later recolonization by mangroves and then saltmarsh. Mangrove and mixed forest mapping since 2010 indicate encroachment into saltmarsh and could be indicating the wetland trying to increase sequestration to keep up with water level rise.

Accretion increased rapidly after the subsidence within inundated areas by 7 mm y^{-1} and appears to relate to an increased accumulation of sediment and organic material. Accretion within the mangrove areas increased slightly due to the subsidence but returned to previous levels of stability. The stable accretion indicates the limited impact the mangrove received due to inundation. The wetland saw an increase in mass accumulation approximately from 0.07 g cm^{-2} y^{-1} to 0.16 g cm^{-2} y^{-1} in inundated areas and an increase from 0.06 g cm^{-2} y^{-1} to 0.14 g cm^{-2} y^{-1} in mangrove areas which indicates the wetlands attempt to keep up with inundation levels. The increased mass accumulation values also indicate an increase in mineral based sediments.
Recent carbon values within the submerged area indicate the wetland has been able to continue to sequester carbon following rapid relative sea-level rise (or subsidence). Sequestration prior to the

subsidence event was 300 g C m^{-2} y^{-1} and following relative sea level rise increased to 627.3 g C m^{-2} y^{-1}, perhaps indicating the ability of the wetland to keep up with water level rise and not become a net carbon emitter. The mangrove area only increased carbon sequestration slightly following inundation from 56 g C m^{-2} y^{-1} to 68 g C m^{-2} y^{-1}. Isotopic values from the submerged cores indicate new carbon material is being sourced from mangrove material likely from nearby mangrove vegetation and possibly from remaining dead mangrove material from mangroves that have drowned. Vegetated zones within the wetland are sequestering material sourced from terrestrial vegetation and an obvious transition to marine carbonate dominated material was seen within each core. The succession from marine to terrestrial carbon sources was also reflected in sediment characteristics that show a transition from central mud basin to fluvial delta and to intertidal terrestrial organic material in the upper core which is reflected in a change from grey muds to coarse sandy organic material followed by an organic dominated horizon. Bulk density and % carbon values also indicate most carbon is located in the upper core and only recalcitrant carbon remains in the fluvial and central mud basin sediments. If similar results are found in other areas of South-East Australia the protection of coastal vegetation for their ability to continue sequestration of carbon following sea level rise should become of high importance.

1.32 **Recommendations**

1. The protection and management of coastal wetlands should become a priority for natural resource managers, scientists, community groups and local and national governments. The sequestration potential of saline coastal wetlands was found in this study to be far greater than terrestrial forest carbon sinks and with increasing sea levels the movement of vegetation up slope will likely cause coastal squeeze in coastal zones where dykes, seawalls, urban developments and other infrastructure exist (Woodroffe et al., 2014).

   Increased studies into the fate of carbon in study sites globally and within other wetlands along the South-East coast of Australia need to be undertaken. It has been shown that on a local scale inundated wetlands that may suffer a reduction in elevation relative to mean water level due to inundation can recover and sequester carbon within available accommodation space. Some studies have been conducted around the world into the sequestration potential of coastal environments in relation to sea level rise but little research has been conducted in sequestration potential of wetlands in Australia. With our current climate and predicted sea-level rise it has become even more of a priority to quantify carbon and determine the fate of carbon.

2. Despite the lack of research concerning the loss of carbon due to inundation, wetlands are evidently good at sequestering carbon and should be protected for this purpose where possible. Blue carbon sinks like the wetland in this study are commodities that should be protected in our future climate scenario as they account for approximately half of global carbon burial in marine sediments (Nellemann et al., 2009). Mangroves, saltmarshes and seagrass meadows have relatively high rates of sediment burial and represent a much smaller area than terrestrial forest but they are still comparable to carbon sinks in terrestrial ecosystem types (McLeod et al., 2011). Chain Valley Bay has given us an opportunity to predict what might happen in similar Australian estuary environments (Roy et al., 2001) and more analysis and comparisons of other estuaries located in South-East Australia should be considered.
3. The capacity of wetlands to adapt to sea level rise shouldn’t be limited by their mitigation potential. Sediment supply and addition should be promoted and activities such as damming that limit these processes should be reduced or engineered to allow for an adequate source of sediment. A lack of adequate sediment supply could lead to a loss in wetland area due to an inability of accretion to match sea-level rise (Mudd et al., 2009, Woodroffe et al., 2014).

REFERENCES

Aecom Australia Pty Ltd, 2011, Submissions Report-Chain Valley Colliery Domains 1 and 2 Continuation Project, LakeCoal Pty Ltd, accessed 4/4/2015.

Australian Bureau of Statistics (2013), accessed 14/10/14. http://www.censusdata.abs.gov.au/census_services/getproduct/census/2011/quickstat/SSC10508?opendocument&navpos=220

Australian Water and Coastal Studies Pty Ltd.(AWACS), J H & E S Laxton Environmental Consultants Pty Ltd, 1995, Lake Macquarie Estuary Process Study-Volume 1 Report, Lake Macquarie City Council, accessed 1/04/15. http://www.livinglakemacquarie.org/files/dwnlds/archives/dnarch07/Estuary%20Process%20Study%20Volume%201.pdf

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R., 2011. The value of estuarine and coastal ecosystem services. *Ecological Monographs* 81, 169-193.

Breithaupt, J. L., J. M. Smoak, T. J. Smith, C. J. Sanders and A. Hoare (2012). Organic carbon burial rates in mangrove sediments: Strengthening the global budget. *Global Biogeochemical Cycles* 26(3).

Brevik, E.C., Homburg, J.A., 2004, A 5000 year record of carbon sequestration from a coastal lagoon and wetland complex, Southern California, USA, *Catena*, 57: 221-232

Bureau of Meteorology (Australian Government) (BOM), 2014a, Climate Data Online (Chain Valley Bay Temperature Search), accessed 22/01/15, http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=123&p_display_type=dailyDataFile&p_startYear=2014&p_c=-754288666&p_stn_num=061412

Bureau of Meteorology (Australian Government) (BOM), 2014b, Climate Data Online (Chain Valley Bay Rainfall Search), accessed 22/01/15, http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=136&p_display_type=dailyDataFile&p_startYear=1988&p_c=-753431836&p_stn_num=061377

Bureau of Meteorology- Australian Government (BOM), 2014, Climate statistics for Australian locations, viewed December 2014, accessed 22/01/15 http://www.bom.gov.au/climate/averages/tables/cw_061273.shtml

Bureau of Meteorology- Australian Governemnt (BOM), 2015, Tide Predictions for Australia, South Pacific and Antarctica, accessed 03/04/15 http://www.bom.gov.au/australia/tides/#!/nsw

Cahoon, D.R., Philippe, F.H., Spencer, T., Reed, D.J., McKee, K.L., Saintilan, N. 2006, Coastal Wetland Vulnerability to Relative Sea-level Rise: Wetland Elevation Trends and Process Controls, *Wetlands and Natural Resources Management Ecological Studies*, 190: 271-292.

Chmura, G.L., Anisfeld, S.C., Cahoon, D.R., Lynch, J.C., 2003, Global carbon sequestration in tidal, saline wetland soils, *Global Biogeochemical Cycles*, 17(4), 1111.

Chmura, G.L, 2013, What do we need to assess the sustainability of the tidal salt marsh carbon sink?, *Ocean and Coastal Management,* 83: 25-31

Choi, Y, Wang, Y, 2001, Vegetation succession and carbon sequestration in a coastal wetland in northwest Florida: Evidence from carbon isotopes, *Global Biogeochemical Cycles*, 15:2 311-319.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1998. The value of the world's ecosystem services and natural capital. *Ecological Economics* 25, 3-15.

Creese, R.G., Glasby, T.M., West, G., Gallen, C., 2009, Mapping the habitats of NSW estuaries, Industry & Investment NSW, Nelson Bay NSW.

Delta Electricity, 2014, Environment-Water, accessed 2/11/14, http://www.de.com.au/Sustainability/Water-and-drought/Water-and-drought/default.aspx

DeLaune, R.D., Nyman, J.A., Patrick, W.H. Jr., 1994, Peat Collapse, Ponding and Wetland loss in a rapidly submerging coastal marsh, *Journal of Coastal Research*, 10: 1021-1030.

DeLaune, R. D., White, J. R., 2012, Will coastal wetlands continue to sequester carbon in response to an increase in global sea level?: a case study of the rapidly subsiding Mississippi river deltaic plain. *Climatic Change* 110(1-2): 297-314.

Department of Planning, 2008, High resolution terrain mapping of the NSW Central and Hunter coasts for assessments of potential climate change impacts: final project report, NSW Government, accessed 9/03/15.

Duarte, C.M., Marba, N., Gacia, E., Fourqurean, J.W., Beggins, J., Barron, C., Apostolaki, E.T., 2010, Seagrass community metabolism: assessing the carbon sink capacity of seagrass meadows, *Global Biogeochemical cycles,* vol 24.

Duarte, C.M., Middleburg, J.J., Caraco, N., 2005, Major role of marine vegetation on the oceanic carbon cycle, *Biogeosciences,* Vol 2: 1-8

Fourqurean, J., B. Johnson, J. B. Kauffman, H. Kennedy, C. Lovelock and et. al., 2014. Conceptualizing the Project and Developing a Field Measurement Plan. In Howard, J., Hoyt, S., Isensee, K., Pidgeon, E., Telszewski, M. (eds.), Coastal Blue Carbon: Methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrass meadows. (pp. 25–38). Arlington, Virginia, USA.

Fourqurean, J., B. Johnson, J. B. Kauffman, H. Kennedy, C. Lovelock and et. al., 2014b. Field Sampling of Soil Carbon Pools in Coastal Ecosystems. In Howard, J., Hoyt, S., Isensee, K., Pidgeon, E., Telszewski, M. (eds.), Coastal Blue Carbon: Methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrass meadows. (pp. 39–66). Arlington, Virginia, USA.

Garofalo, D., 1980, The influence of wetland vegetation on tidal stream channel migration and morphology." *Estuaries* 3(4): 258-270.

Gehrels, W. R., Hayward B. W., Newnham R. M. and Southall, K. E., 2008. A 20th century acceleration of sea-level rise in New Zealand. *Geophysical Research Letters* 35(2): L02717.

Guest, M.A., Connolly, R.M., Longeragan, N.R., 2004, Within and among-site variability in $\delta^{13}C$ and $\delta^{13}N$ for three estuarine producers, Sporobolus virginicus, Zostera capricorni and epiphytpes of Z. capricorni, *Aquatic Botany*, 87-94.

Hemminga, M.A, Mateo, M.A., 1996, Stable carbon isotopes in seagreasses: variability in ratios and use in ecological studies, *Marine Ecology Progress Series*, Vol 140: 285-298.

Haslett, S. K. (2000). *Coastal Systems*, Routledge.

Howard, J., Isensee, K., Kennedy, H., Pidgeon, E., Telszewski, M., 2014. Why Measure Carbon Stocks. In Howard, J., Hoyt, S., Isensee, K., Pidgeon, E., Telszewski, M. (eds.), Coastal Blue Carbon: Methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrass meadows. (pp. 15–24). Arlington, Virginia, USA.

IPCC, 2014, Climate Change 2014 Synthesis Report, The core writing team, Rachuri, RK., Myer, L. (eds).

Jensen, John R., 2007, Remote Sensing of the Environment: An Earth Resource Perspective, 2nd Ed., Upper Saddle River, NJ: Prentice Hall.

Kirwan, M.L. & Mudd, S.M., 2012 Response of salt-marsh carbon accumulation to climate change, *Nature* 489(7417):550-553.

Kayranli, B. S., M. & Mustafa, A. & Hedmark, A., 2010, Carbon Storage and Fluxes within Freshwater Wetlands: a Critical Review, *Wetlands* (30): 111-124.

Landcare Resource Office (LRO), 2009, A case study of Saltmarsh Restoration In Lake Macquarie-Enhance Marine Shoreline, Enhance Foreshore Vegetation. Community support program, accessed 13/02/15 http://www.lakemacquarielandcare.org/Files/Uploads/File/Resources/Case%20Study%20of%20Saltmarsh%20sites%20in%20Lake%20Macquarie.pdf

LakeCoal, 2012, Chain Valley Colliery, accessed 8/02/15, http://www.chainvalleymine.com.au/

LakeCoal, 2013, Chain Valley Colliery Annual Review 2012-2013, accessed 8/02/15, http://www.chainvalleymine.com.au/wp-content/uploads/2012/04/RPT-D-17896-Annual-Review-12-13-Final.pdf

Leonard, L. A. and A. L. Croft, 2006, The effect of standing biomass on flow velocity and turbulence in Spartina alterniflora canopies, *Estuarine, Coastal and Shelf Science* 69(3–4): 325-336.

Macreadie, P. I., Allen, K., Kelaher, B. P., Ralph, P. J., Skilbeck, C. G., 2012, Paleoreconstruction of estuarine sediments reveal human-induced weakening of coastal carbon sinks, *Global Change Biology* 18(3): 891-901.

Macreadie, P. I., Hughes, A. R. Kimbro, D. L., 2013, Loss of 'Blue Carbon' from Coastal Salt Marshes Following Habitat Disturbance, *PLoS ONE* 8(7): e69244.

Masselink, G., Gehrels, R., 2014, Coastal Environments and Global Change. Hoboken, *Wiley*.

Mcnally, G. H., Branagan, D.F., 2014, Geotechnical consequences of the Newcastle Coal Measures rocks, *Australian Journal of Earth Sciences* 61(3): 363-374.

Mitsch, W., Bernal, B., Nahlik, A., Mander, Ü., Zhang, L., Anderson, C., Jørgensen, S., Brix, H., 2013, Wetlands, carbon, and climate change, *Landscape Ecology* 28(4): 583-597.

O'Leary, M. H., 1988, Carbon Isotopes in Photosynthesis, *Bioscience* 38(5): 328.

Mcleod, E., Chmura, G.L., Bouillon, S., Salm, R., Bjork, Mats, Duarte, C.M., Lovelock, C.E., Schlesinger, W.H., Silliman, B.R., 2011, A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2, *The Ecological Society of America*

Morton, R, Syme, B., Pocock, J., McAlister, T., Rose, C., 1996, Lake Macquarie Estaury Management Study Volume 2-lake management issues

Mudd, S.M., Howell, S.M., Morris, J.T., 2009, Impact of dynamic feedbacks between sedimentation, sea-level rise, and biomass production on near-surface marsh straigraphy and carbon accumulation, *Estuarine, Coastal and Shelf Science*, 1-13.

Nellemann, C., Corcoran, E., Duarte, C. M., Valdés, L., De Young, C., Fonseca, L., Grimsditch, G. (Eds). 2009. Blue Carbon. A Rapid Response Assessment. United Nations Environment Programme, GRID-Arendal, www.grida.no

Novatel, 2014, Real-Time Kinematic (RTK), accessed 07/02/15,

http://www.novatel.com/an-introduction-to-gnss/chapter-4-advanced-gnss-concepts/

NSW Government Mine Subsidence Board (MSB), 2007, 1949 – Today, accessed 18/2/15, http://www.minesub.nsw.gov.au/templates/mine_subsidence_board.aspx?edit=false&pageID=3877,

NSW Mine Subsidence Board (MSB), 1991, Chain Valley Bay Restoration Project: Special Report, Mine Subsidence Board, Newcastle NSW.

NSW Government Office of Environment and Heritage (OEH), 2013, Lake Macquarie-Physical characteristics, accessed 20/10/14,

http://www.environment.nsw.gov.au/estuaries/stats/LakeMacquarie.htm

NSW Government Department of Trade & Investment & Resources & Energy (NSW TIRE), Map of NSW Coalfields, accessed 23/11/14, http://www.resourcesandenergy.nsw.gov.au/landholders-and-community/geoscience-for-landholders/coalfields

Oceanscan, 2014, Odom Echotrac^{TM} MkIII Model, accessed 1/04/15 http://www.oceanscan.net/gallery/PDFs/ODOMECHOTRAC.PDF

Oliver, T.S.N., Rogers, K., Chafer, C.J., Woodroffe, C.D., 2012, Measuring, mapping and modelling: an integrated approach to the management of mangrove and saltmarsh in the Minnamurra River estuary, southeast Australia, *Wetlands Ecol Manage*, Is 20: 353-371

OzCoasts (Geoscience Australia), 1998, Lake Macquaire (NSW) (estuary search), accessed 4/10/14, http://www.ozcoasts.gov.au/search_data/detail_result.jsp

OzCoasts. (2013), Typology: Estuaries, accessed 12/12/14, http://www.ozcoasts.gov.au/conceptual_mods/typology.jsp.

Office of Environment. and Heritage (OEH), 2013, Lake Macquarie., accessed 20/10/2014, http://www.environment.nsw.gov.au/estuaries/stats/LakeMacquarie.htm

Oldfield, F., Appleby, P.G., 1984. Empirical testing of 210Pb-dating models for lake sediments. In: Hayworth EY and Lund JWG (Eds). Lake Sediments and Environmental History. Leicester University Press, 93-124.

Pendleton, L., Donato, D.C., Murray, B.C., Crooks, S., Jenkins, W.A., et al, 2012, Estimating Global "Blue Carbon" Emissions from Conversion and Degradation of Vegetated Coastal Ecosystems, *PLoS ONE* 7(9).

Wolanski, E., Brinson, M.M., Cahoon, D.R., Perillo, G.M.E. (2009). In Perillo, G. M. E., Wolanski, E., Cahoon, D.R., Brinson, M.M. (eds) *Coastal wetlands: an integrated ecosystem approach*. Amsterdam; London, Elsevier Science.

Piola, R.F., Suthers, I.M., Rissik, D, 2008, Carbon and nitrogen stable isotope analysis indicates freshwater shrimp Paratya australiensis Kemp, 1917 (Atyidae) assimilate cyanobacterial accumulations, *Hydrobiologia*, Vol 608: 121-132.

Rogers, K., Wilton, K.M., Saintilan, N., 2006, Vegetation change and surface elevation dynamics in estuarine wetlands of southeast Australia, *Estuarine Coastal and Shelf Science*, Is 66: 559-569

Roy, P. S., Williams, R. J., Jones, A. R., Yassini, I., Gibbs, P. J., Coates, B., West, R. J., Scanes, P. R., Hudson, J. P., Nichol, S., 2001, Structure and Function of South-east Australian Estuaries, *Estuarine, Coastal and Shelf Science* 53(3): 351-384.

Saintilan, N., 2004, Relationships between estuarine geomorphology, wetland extent and fish landings in New South Wales estuaries, *Estuarine, Coastal and Shelf Science 61*(4): 591-601.

Ryan, D.A., Heap, A.D., Radke, L., Heggie, D.T., 2003, Conceptual models of Australia's estuaries and coastal waterways: applications for coastal resource management, *Geoscience Australia*, Record 2003/09, 136 pp.

Saintilan, N, Rogers, K, Mazumder, D, Woodroffe, C, 2003, Allochthonous and autochthonous contributions to carbon accumulation and carbon store in southeastern Australian coastal wetlands, *Estuarine, Coastal and Shelf Science*, 128 84-92.

Saintilan, N., Williams, R.J., 1999, Mangrove Transgression into saltmarsh environments in south-east Australia, *Global Ecology and Biogeography*, Is 8: 117-124

Sean Ulm, 2006, Coastal Themes (Terra Australis 24) An Archaeology of the Southern Curtis Coast, Queensland, ANU Press, Canberra ACT, Australia, Chapter 4. http://press.anu.edu.au/wp-content/uploads/2011/06/ch047.pdf

Short, A.D., Woodroffe, C.D., 2009, The Coast of Australia, Cambridge University Press, New York, USA

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L., 2007, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007.

Stumpf, R. P., 1983, The process of sedimentation on the surface of a salt marsh, *Estuarine, Coastal and Shelf Science* 17(5): 495-508.

Underwood, G. J. C. and D. M. Paterson, 1993, Recovery of intertidal benthic diatoms after biocide treatment and associated sediment dynamics, *Journal of the Marine Biological Association of the United Kingdom* 73(01): 25-45.

White, N. J., I. D. Haigh, J. A. Church, T. Koen, C. S. Watson, T. R. Pritchard, P. J. Watson, R. J. Burgette, K. L. McInnes, Z.-J. You, X. Zhang and P. Tregoning 2014, Australian sea levels—Trends, regional variability and influencing factors, *Earth-Science Reviews* 136(0): 155-174.

Watterson, E.K., Burston, J.M., Stevens, H., Messiter, D.J., 2009, The Hydraulic and Morphological Response of a large coastal lake to rising sea levels, *Coastal Conference 2010*,

Wilton, K.M., Saintilan, N., 2000. Protocols for mangrove and saltmarsh habitat mapping. Australian Catholic University Coastal Wetlands Unit Technical Report 2000/01. Produced for the Estuaries Branch, NSW Department of Land and Water Conservation, Sydney. http://dlibrary.acu.edu.au/digitaltheses/public/adt-acuvp29.29082005/03chapter_3.pdf

Witt,C., Charteris, A., Andrews, M., Syme, B.,1996, Lake Macquarie Estuary Management Study Volume 1 - Report on Entrance Channel Issues, WBM Oceanics Australia.

Woodroffe, C. D., 2003, Coasts: form, process, and evolution. New York, USA, Cambridge University Press.

Woodroffe, C.D., Lovelock, C.E., Rogers, K., 2014, 11 Mangrove Shorelines, in Gerd Masselink and Roland Gehrels (eds), *Coastal Environments and Global Change*, John Wiley & Sons, Hoboken, p251-267.

Yee, D.M., Geddes, A.J., Simpson, C.G., 1991, Lloyd avenue, chain valley bay mine subsidence restoration, stage 1-a case study, Second Triennial conference on Buildings and structures subject to mine subsidence, Mine Subsidence Technological society.

Yang, S. L., 1998, The role of Scirpus marsh in attenuation of hydrodynamics and retention of fine sediment in the Yangtze estuary, *Estuarine, Coastal and Shelf Science* 47(2): 227-233.

APPENDIX A – RADIOMETRIC ISOTOPE LEAD-210 REPORT.

Please refer to excel file called: ANSTO Pb210 dating results CVB.

APPENDIX B – CARBON ISOTOPE RESLUTS PROVIDED BY ANSTO

Excel file format has been included outside of this document. Please refer to excel file called: ANSTO carbon isotope results CVB.

Australian Government | ansto Nuclear-based science benefiting all Australians

Institute for Environmental Research

Stable Isotope Analysis Report

Final Report 23.03.2015

Client Details

Company Name:	ANSTO
Address:	Locked Bag 2001, Kirrawee DC NSW 2232
Contact Name:	Debashish Mazumder & Kerrylee Rogers
Tel:	9219
Email:	dma@ansto.gov.au
Purchase Order No.	N/A

Sample Details

Number:	224
Material:	Sediment

Sample Tracking

LIMS Batch Number:	2014-0368J
Registration Date:	17/12/2014

Analysis Details

Isotope(s) :	$\delta^{15}N$
	$\delta^{13}C$
Method(s):	$\delta^{15}N$ by combustion
	$\delta^{13}C$ by combustion
Initial Report Date:	23/03/2015

Name: Barbora Gallagher

Signature: B Gallagher

Date: 23/03/2015

Analysis of $\delta^{13}C$ and $\delta^{15}N$

This report contains determinations of relative difference of isotope ratios, δ, of ($^{13}C/^{12}C$) and ($^{15}N/^{14}N$), elsewhere referred to as $\delta^{13}C$ and $\delta^{15}N$ respectively . The values will be reported as parts per thousand (‰ or per mil).

Samples were run using an established on-line combustion, continuous-flow IRMS method.

In brief, the crushed and dried samples are weighed into tin capsules and introduced sequentially into an elemental analyser (Thermo Fisher Flash 2000 HT EA) using an autosampler. Each sample is then combusted into CO_2 and N_2 in a combustion furnace (silvered cobaltous/ic oxide, chromium oxide, quartz chips and quartz wool) at 1020ºC before being transferred with a helium carrier gas (100 mL/min) into a reduction furnace (copper) at 600ºC, where any excess nitrous oxides are converted into N_2 and excess O_2 is removed. The analyte gases are then passed through a water trap before the CO_2 and N_2 are separated by a GC column at 40ºC. The gases are then transferred to a Thermo Fisher Conflo IV and into a Thermo Fisher Delta V Plus isotope ratio mass spectrometer for $\delta^{13}C$ and $\delta^{15}N$ measurements.

The data reported relative to IAEA secondary standards that have been certified relative to VPDB for carbon and air for nitrogen. A two point calibration is employed to normalise the data, utilising standards that bracket the samples being analysed. Two quality control references were also included in each run; see page 5 for details of the standards used.

Results are accurate to 1% for both N % and C % and +/- 0.3 permil for $\delta^{15}N$ and $\delta^{13}C$.

$$\delta^{13}C = \delta(^{13}C/^{12}C)_{P/\mathrm{reference}} = \frac{R\left(^{13}C/^{12}C\right)_P - R\left(^{13}C/^{12}C\right)_{\mathrm{reference}}}{R\left(^{13}C/^{12}C\right)_{\mathrm{reference}}}$$

$$\delta^{15}N = \delta(^{15}N/^{14}N)_{P/\mathrm{reference}} = \frac{R\left(^{15}N/^{14}N\right)_P - R\left(^{15}N/^{14}N\right)_{\mathrm{reference}}}{R\left(^{15}N/^{14}N\right)_{\mathrm{reference}}}$$

Reference: Ohlsson K, Wallmark P. 1999. Novel calibration with correction for drift and non-linear response for continuous flow isotope ratio mass spectrometry applied to the determination of delta N-15, total nitrogen, delta C-13 and total carbon in biological material. Analyst 124: 571–577.

B Gallagher

LIMS Number	Client Identification	Sample No.	Nitrogen Data N %	Nitrogen Data $\delta^{15}N_{AIR}$ ‰	Carbon Data C %	Carbon Data $\delta^{13}C_{V-PDB}$ ‰	Sample Comments
2014/0368J-1	SW1.1, ACIDIFIED	1	-	-	21.0	-29.0	SA15FEB26
2014/0368J-2	SW1.2, ACIDIFIED	2	-	-	21.1	-28.4	SA15FEB26
2014/0368J-3	SW1.3, ACIDIFIED	3	-	-	7.0	-26.4	SA15FEB26
2014/0368J-4	SW1.4, ACIDIFIED	4	-	-	1.0	-17.7	SA15FEB26
2014/0368J-5	SW1.5, ACIDIFIED	5	-	-	0.7	-12.7	SA15FEB26
2014/0368J-5(2)	SW1.5, ACIDIFIED	5	-	-	0.7	-11.9	SA15MAR04(1)
2014/0368J-6	SW1.6, ACIDIFIED	6	-	-	1.4	-18.1	SA15FEB27
2014/0368J-7	SW1.7, ACIDIFIED	7	-	-	1.0	-7.3	SA15FEB27
2014/0368J-8	SW1.8, ACIDIFIED	8	-	-	0.6	-11.1	SA15FEB27
2014/0368J-9	SW1.9, ACIDIFIED	9	-	-	1.4	-24.8	SA15FEB27
2014/0368J-10	SW1.10, ACIDIFIED	10	-	-	1.3	-25.2	SA15FEB27
2014/0368J-11	SW1.11, ACIDIFIED	11	-	-	3.0	-26.1	SA15FEB27
2014/0368J-12	SW1.12, ACIDIFIED	12	-	-	2.2	-27.2	SA15FEB27
2014/0368J-13	SW1.13, ACIDIFIED	13	-	-	1.6	-27.2	SA15FEB27
2014/0368J-14	SW1.14, ACIDIFIED	14	-	-	1.7	-24.3	SA15FEB27
2014/0368J-15	MN2.1, ACIDIFIED	15	-	-	17.5	-25.2	SA15FEB27
2014/0368J-16	MN2.2, ACIDIFIED	16	-	-	30.7	-26.7	SA15FEB27
2014/0368J-16(2)	MN2.2, ACIDIFIED	16	-	-	31.5	-26.8	SA15MAR04(1)
2014/0368J-17	MN2.3, ACIDIFIED	17	-	-	26.5	-24.2	SA15FEB27
2014/0368J-18	MN2.4, ACIDIFIED	18	-	-	3.1	-18.7	SA15FEB27
2014/0368J-19	MN2.5, ACIDIFIED	19	-	-	0.7	-4.1	SA15FEB27
2014/0368J-20	MN2.6, ACIDIFIED	20	-	-	0.7	-9.4	SA15FEB27
2014/0368J-21	MN2.7, ACIDIFIED	21	-	-	2.2	-11.1	SA15FEB27
2014/0368J-22	MN2.8, ACIDIFIED	22	-	-	1.7	-15.2	SA15FEB26
2014/0368J-22(2)	MN2.8, ACIDIFIED	22	-	-	2.0	-14.5	SA15MAR04(1)
2014/0368J-23	MN2.9, ACIDIFIED	23	-	-	1.4	-12.0	SA15FEB26
2014/0368J-24	CAS1.1, ACIDIFIED	24	-	-	38.1	-28.2	SA15MAR04(1)
2014/0368J-25	CAS1.2, ACIDIFIED	25	-	-	19.7	-28.1	SA15MAR04(1)
2014/0368J-26	CAS1.3, ACIDIFIED	26	-	-	20.2	-27.6	SA15MAR04(1)
2014/0368J-27	CAS1.4, ACIDIFIED	27	-	-	3.7	-27.0	SA15JAN19
2014/0368J-28	CAS1.5, ACIDIFIED	28	-	-	0.3	-23.8	SA15MAR03
2014/0368J-29	CAS1.6, ACIDIFIED	29	-	-	0.7	-11.9	SA15MAR03
2014/0368J-30	CAS1.7, ACIDIFIED	30	-	-	0.7	-22.5	SA15MAR03
2014/0368J-31	CAS1.8, ACIDIFIED	31	-	-	0.6	-22.7	SA15MAR03
2014/0368J-32	CAS1.9, ACIDIFIED	32	-	-	1.1	-22.1	SA15MAR03
2014/0368J-33	CAS1.10, ACIDIFIED	33	-	-	1.3	-24.7	SA15MAR03
2014/0368J-34	CAS1.11, ACIDIFIED	34	-	-	3.6	-27.6	SA15MAR03
2014/0368J-35	CAS1.12, ACIDIFIED	35	-	-	2.3	-28.7	SA15MAR03
2014/0368J-35(2)	CAS1.12, ACIDIFIED	35	-	-	2.3	-28.5	SA15MAR04(1)
2014/0368J-36	CAS1.13, ACIDIFIED	36	-	-	1.8	-28.3	SA15MAR03
2014/0368J-37	CAS1.14, ACIDIFIED	37	-	-	1.1	-28.1	SA15MAR03
2014/0368J-38	SUB D 1.1, ACIDIFIED	38	-	-	16.5	-24.7	SA15MAR03
2014/0368J-39	SUB D 1.2, ACIDIFIED	39	-	-	10.7	-23.2	SA15MAR03
2014/0368J-40	SUB D 1.3, ACIDIFIED	40	-	-	0.5	-23.4	SA15MAR03
2014/0368J-41	SUB D 1.4, ACIDIFIED	41	-	-	0.4	-10.4	SA15MAR03

Legend: Take results as guide only. The Nitrogen values were at the limit of detection.

BGallagher

Australian Government

ansto
Nuclear-based science benefiting all Australians

LIMS Number	Client Identification	Sample No.	Nitrogen Data: N %	Nitrogen Data: $\delta^{15}N_{AIR}$ ‰	Carbon Data: C %	Carbon Data: $\delta^{13}C_{V\text{-}PDB}$ ‰	Sample Comments
2014/0368J-42	SUB D 1.5, ACIDIFIED	42	-	-	0.7	-13.0	SA15MAR03
2014/0368J-43	SUB D 1.6, ACIDIFIED	43	-	-	0.8	-21.2	SA15MAR04(1)
2014/0368J-44	SUB D 1.7, ACIDIFIED	44	-	-	1.3	-9.4	SA15FEB27
2014/0368J-45	SUB D 1.8, ACIDIFIED	45	-	-	1.1	-14.7	SA15MAR04(1)
2014/0368J-46	SUB D 1.9, ACIDIFIED	46	-	-	1.3	-13.1	SA15FEB27
2014/0368J-47	SUB D 1.10, ACIDIFIED	47	-	-	1.8	-11.1	SA15FEB27
2014/0368J-48	SUB D 1.11, ACIDIFIED	48	-	-	1.3	-11.3	SA15FEB27
2014/0368J-48(2)	SUB D 1.11, ACIDIFIED	48	-	-	1.3	-10.9	SA15MAR04(1)
2014/0368J-49	SUB D 1.12, ACIDIFIED	49	-	-	2.2	-14.0	SA15FEB27
2014/0368J-50	SUB D 1.13, ACIDIFIED	50	-	-	2.0	-13.1	SA15FEB27
2014/0368J-51	SUB D 1.14, ACIDIFIED	51	-	-	1.8	-15.4	SA15FEB27
2014/0368J-52	SUB A 1.1, ACIDIFIED	52	-	-	9.2	-23.2	SA15MAR04(1)
2014/0368J-53	SUB A 1.2, ACIDIFIED	53	-	-	17.6	-23.7	SA15MAR04(1)
2014/0368J-54	SUB A 1.3, ACIDIFIED	54	-	-	0.6	-16.8	SA15MAR04(1)
2014/0368J-55	SUB A 1.4, ACIDIFIED	55	-	-	1.8	-22.3	SA15FEB27
2014/0368J-56	SUB A 1.5, ACIDIFIED	56	-	-	0.6	-17.3	SA15MAR04(1)
2014/0368J-57	SUB A 1.6, ACIDIFIED	57	-	-	1.7	-19.3	SA15FEB27
2014/0368J-58	SUB A 1.7, ACIDIFIED	58	-	-	1.6	-15.8	SA15FEB27
2014/0368J-59	SUB A 1.8, ACIDIFIED	59	-	-	1.8	-19.0	SA15FEB27
2014/0368J-60	SUB A 1.9, ACIDIFIED	60	-	-	2.0	-17.8	SA15FEB27
2014/0368J-61	SUB A 1.10, ACIDIFIED	61	-	-	2.5	-18.2	SA15FEB27
2014/0368J-62	FAR 1.1, ACIDIFIED	62	-	-	38.1	-28.3	SA15MAR04(1)
2014/0368J-63	FAR 1.2, ACIDIFIED	63	-	-	23.4	-27.1	SA15MAR04(1)
2014/0368J-64	FAR 1.3, ACIDIFIED	64	-	-	9.8	-24.6	SA15MAR04(1)
2014/0368J-65	FAR 1.4, ACIDIFIED	65	-	-	1.5	-19.8	SA15FEB27
2014/0368J-66	FAR 1.5, ACIDIFIED	66	-	-	3.2	-26.6	SA15FEB27
2014/0368J-67	FAR 1.6, ACIDIFIED	67	-	-	0.6	-18.0	SA15MAR03
2014/0368J-68	FAR 1.7, ACIDIFIED	68	-	-	1.1	-9.1	SA15MAR03
2014/0368J-69	FAR 1.8, ACIDIFIED	69	-	-	0.7	-7.5	SA15MAR03
2014/0368J-70	FAR 1.9, ACIDIFIED	70	-	-	0.6	-17.4	SA15MAR03
2014/0368J-71	FAR 1.10, ACIDIFIED	71	-	-	1.0	-12.3	SA15MAR03
2014/0368J-72	FAR 1.11, ACIDIFIED	72	-	-	0.9	-22.8	SA15MAR03
2014/0368J-73	FAR 1.12, ACIDIFIED	73	-	-	1.2	-24.8	SA15FEB26
2014/0368J-73(2)	FAR 1.12, ACIDIFIED	73	-	-	1.1	-24.7	SA15MAR04(1)
2014/0368J-74	FAR 1.13, ACIDIFIED	74	-	-	2.1	-26.6	SA15FEB26
2014/0368J-75	FAR 1.14, ACIDIFIED	75	-	-	1.2	-28.6	SA15FEB26
2014/0368J-76	FAR 1.15, ACIDIFIED	76	-	-	0.4	-27.0	SA15MAR03
2014/0368J-77	FAR 1.16, ACIDIFIED	77	-	-	0.4	-26.2	SA15MAR03
2014/0368J-78	FAR 1.17, ACIDIFIED	78	-	-	0.4	-25.5	SA15MAR03
2014/0368J-79	MAN1.1, ACIDIFIED	79	-	-	29.0	-27.4	SA15MAR03
2014/0368J-80	MAN1.2, ACIDIFIED	80	-	-	25.0	-27.1	SA15MAR03
2014/0368J-81	MAN1.3, ACIDIFIED	81	-	-	23.6	-26.9	SA15MAR03
2014/0368J-82	MAN1.4, ACIDIFIED	82	-	-	3.1	-10.9	SA15FEB26
2014/0368J-83	MAN1.5, ACIDIFIED	83	-	-	0.6	-22.2	SA15MAR03
2014/0368J-84	MAN1.6, ACIDIFIED	84	-	-	0.2	-23.9	SA15MAR03

Legend: Take results as guide only. The Nitrogen values were at the limit of detection.

B Gallagher

Australian Government

ansto

Nuclear-based science benefiting all Australians

LIMS Number	Client Identification	Sample No.	Nitrogen Data N %	Nitrogen Data $\delta^{15}N_{AIR}$ ‰	Carbon Data C %	Carbon Data $\delta^{13}C_{V\text{-}PDB}$ ‰	Sample Comments
2014/0368J-85	MAN1.7, ACIDIFIED	85	-	-	0.7	-6.1	SA15MAR03
2014/0368J-86	MAN1.8, ACIDIFIED	86	-	-	0.6	-6.5	SA15MAR03
2014/0368J-87	MAN1.9, ACIDIFIED	87	-	-	1.0	-12.2	SA15MAR03
2014/0368J-88	MAN1.10, ACIDIFIED	88	-	-	1.3	-13.1	SA15FEB26
2014/0368J-89	MAN1.11, ACIDIFIED	89	-	-	1.5	-19.1	SA15FEB26
2014/0368J-90	MAN1.12, ACIDIFIED	90	-	-	1.6	-24.0	SA15FEB26
2014/0368J-91	MAN1.13, ACIDIFIED	91	-	-	2.8	-27.6	SA15FEB26
2014/0368J-91(2)	MAN1.13, ACIDIFIED	91	-	-	2.7	-28.0	SA15MAR04(1)
2014/0368J-92	CAS2.1, ACIDIFIED	92	-	-	37.9	-29.5	SA15MAR03
2014/0368J-93	CAS2.2, ACIDIFIED	93	-	-	27.1	-29.1	SA15MAR03
2014/0368J-94	CAS2.3, ACIDIFIED	94	-	-	6.4	-26.5	SA15FEB26
2014/0368J-95	CAS2.4, ACIDIFIED	95	-	-	2.6	-26.3	SA15FEB26
2014/0368J-96	CAS2.5, ACIDIFIED	96	-	-	0.3	-20.4	SA15MAR03
2014/0368J-97	CAS2.6, ACIDIFIED	97	-	-	0.4	-12.5	SA15MAR03
2014/0368J-98	CAS2.7, ACIDIFIED	98	-	-	0.9	-19.5	SA15MAR03
2014/0368J-99	CAS2.8, ACIDIFIED	99	-	-	1.2	-22.7	SA15FEB26
2014/0368J-100	SM1.1, ACIDIFIED	100	-	-	31.3	-26.8	SA15MAR03
2014/0368J-101	SM1.2, ACIDIFIED	101	-	-	20.8	-27.2	SA15MAR03
2014/0368J-102	SM1.3, ACIDIFIED	102	-	-	4.1	-23.9	SA15FEB26
2014/0368J-103	SM1.4, ACIDIFIED	103	-	-	0.6	-12.6	SA15MAR03
2014/0368J-104	SM1.5, ACIDIFIED	104	-	-	0.3	-13.6	SA15MAR03
2014/0368J-105	SM1.6, ACIDIFIED	105	-	-	2.0	-5.7	SA15FEB26
2014/0368J-106	SM1.7, ACIDIFIED	106	-	-	2.2	-15.7	SA15FEB26
2014/0368J-107	SM1.8, ACIDIFIED	107	-	-	2.0	-13.5	SA15FEB26
2014/0368J-107(2)	SM1.8, ACIDIFIED	107	-	-	1.9	-13.2	SA15MAR04(1)
2014/0368J-108	PEAT 1.1, ACIDIFIED	108	-	-	28.3	-24.7	SA15MAR03
2014/0368J-109	PEAT 1.2, ACIDIFIED	109	-	-	27.6	-21.0	SA15MAR04(1)
2014/0368J-110	PEAT 1.3, ACIDIFIED	110	-	-	24.7	-21.7	SA15MAR04(1)
2014/0368J-111	PEAT 1.4, ACIDIFIED	111	-	-	19.4	-19.0	SA15MAR04(1)
2014/0368J-112	PEAT 1.5, ACIDIFIED	112	-	-	19.2	-24.7	SA15MAR04(1)
2014/0368J-113	SW1.1	113	0.8	1.7	-	-	SA15MAR04(2)
2014/0368J-114	SW1.2	114	0.8	1.4	-	-	SA15MAR04(2)
2014/0368J-115	SW1.3	115	0.6	2.3	-	-	SA15MAR04(2)
2014/0368J-115(2)	SW1.3	115	0.7	2.5	-	-	SA15MAR20
2014/0368J-116	SW1.4	116	<0.1	0.7 ± 0.7	-	-	SA15MAR04(2)
2014/0368J-117	SW1.5	117	<0.1	0.3 ± 1.4	-	-	SA15MAR04(2)
2014/0368J-118	SW1.6	118	<0.1	-0.3 ± 0.7	-	-	SA15MAR04(2)
2014/0368J-119	SW1.7	119	<0.1	0.9 ± 1.4	-	-	SA15MAR04(2)
2014/0368J-120	SW1.8	120	<0.1	-3.4 ± 1.6	-	-	SA15MAR04(2)
2014/0368J-121	SW1.9	121	<0.1	1.1 ± 1.0	-	-	SA15MAR04(2)
2014/0368J-122	SW1.10	122	<0.1	0.2 ± 1.1	-	-	SA15MAR04(2)
2014/0368J-123	SW1.11	123	0.1	1.1 ± 0.4	-	-	SA15MAR04(2)
2014/0368J-123(2)	SW1.11	123	0.1	1.5 ± 0.4	-	-	SA15MAR20
2014/0368J-124	SW1.12	124	<0.1	0.2 ± 0.7	-	-	SA15MAR06
2014/0368J-125	SW1.13	125	<0.1	-0.9 ± 0.9	-	-	SA15MAR06

Legend: Take results as guide only. The Nitrogen values were at the limit of detection.

BGallagher

AUSTRALIAN NUCLEAR SCIENCE AND TECHNOLOGY ORGANISATION
New Illawarra Road, Lucas Heights (Locked Bag 2001, Kirrawee DC NSW 2232) T +61 2 9717 3111 F +61 2 9543 5097
www.ansto.gov.au

Australian Government

ansto
Nuclear-based science benefiting all Australians

LIMS Number	Client Identification	Sample No.	Nitrogen Data: N %	Nitrogen Data: $\delta^{15}N_{AIR}$ ‰	Carbon Data: C %	Carbon Data: $\delta^{13}C_{V\text{-}PDB}$ ‰	Sample Comments
2014/0368J-126	SW1.14	126	<0.1	-0.9 ± 1.0	-	-	SA15MAR06
2014/0368J-127	MN2.1	127	1.0	1.3	-	-	SA15MAR20
2014/0368J-128	MN2.2	128	1.3	0.1	-	-	SA15MAR20
2014/0368J-129	MN2.3	129	1.3	1.7	-	-	SA15MAR20
2014/0368J-130	MN2.4	130	0.1	1.4	-	-	SA15MAR06
2014/0368J-130(2)	MN2.4	130	0.1	1.9	-	-	SA15MAR20
2014/0368J-131	MN2.5	131	<0.1		-	-	SA15MAR06
2014/0368J-132	MN2.6	132	<0.1	1.3 ± 1.5	-	-	SA15MAR06
2014/0368J-133	MN2.7	133	0.1	2.1	-	-	SA15MAR06
2014/0368J-134	MN2.8	134	0.1	2.3	-	-	SA15MAR06
2014/0368J-135	MN2.9	135	0.1	1.3 ± 0.5	-	-	SA15MAR06
2014/0368J-136	CAS1.1	136	1.5	0.6	-	-	SA15MAR20
2014/0368J-137	CAS1.2	137	0.7	0.5	-	-	SA15MAR06
2014/0368J-138	CAS1.3	138	0.7	1.3	-	-	SA15MAR06
2014/0368J-139	CAS1.4	139	0.3	2.4	-	-	SA15MAR06
2014/0368J-140	CAS1.5	140	<0.1	2.0 ± 1.5	-	-	SA15MAR06
2014/0368J-141	CAS1.6	141	<0.1	0.8 ± 1.3	-	-	SA15MAR06
2014/0368J-142	CAS1.7	142	<0.1	0.9 ± 1.1	-	-	SA15MAR06
2014/0368J-143	CAS1.8	143	<0.1	1.7 ± 1.2	-	-	SA15MAR06
2014/0368J-143(2)	CAS1.8	143	<0.1		-	-	SA15MAR20
2014/0368J-144	CAS1.9	144	<0.1	1.1 ± 0.9	-	-	SA15MAR06
2014/0368J-145	CAS1.10	145	<0.1	2.0 ± 0.9	-	-	SA15MAR06
2014/0368J-146	CAS1.11	146	0.1	1.0	-	-	SA15MAR06
2014/0368J-147	CAS1.12	147	0.1	-0.2 ± 0.4	-	-	SA15MAR06
2014/0368J-148	CAS1.13	148	<0.1	0.01 ± 0.7	-	-	SA15MAR06
2014/0368J-149	CAS1.14	149	<0.1	-2.0 ± 1.1	-	-	SA15MAR06
2014/0368J-150	SUB D 1.1	150	0.8	2.2	-	-	SA15MAR06
2014/0368J-151	SUB D 1.2	151	0.6	1.7	-	-	SA15MAR06
2014/0368J-152	SUB D 1.3	152	<0.1		-	-	SA15MAR06
2014/0368J-153	SUB D 1.4	153	<0.1		-	-	SA15MAR06
2014/0368J-154	SUB D 1.5	154	<0.1		-	-	SA15MAR06
2014/0368J-155	SUB D 1.6	155	<0.1	0.8 ± 1.0	-	-	SA15MAR06
2014/0368J-156	SUB D 1.7	156	<0.1	1.2 ± 1.0	-	-	SA15MAR06
2014/0368J-157	SUB D 1.8	157	<0.1	2.0 ± 0.6	-	-	SA15MAR06
2014/0368J-157(2)	SUB D 1.8	157	0.1	1.5 ± 0.7	-	-	SA15MAR20
2014/0368J-158	SUB D 1.9	158	<0.1	2.6 ± 0.6	-	-	SA15MAR06
2014/0368J-159	SUB D 1.10	159	0.1	1.3	-	-	SA15MAR20
2014/0368J-160	SUB D 1.11	160	<0.1	2.3 ± 0.7	-	-	SA15MAR20
2014/0368J-161	SUB D 1.12	161	0.1	1.5	-	-	SA15MAR20
2014/0368J-162	SUB D 1.13	162	0.1	1.8	-	-	SA15MAR20
2014/0368J-163	SUB D 1.14	163	0.1	1.8	-	-	SA15MAR20
2014/0368J-164	SUB A 1.1	164	0.6	2.1	-	-	SA15MAR20
2014/0368J-165	SUB A 1.2	165	1.0	2.1	-	-	SA15MAR20
2014/0368J-166	SUB A 1.3	166	<0.1		-	-	SA15MAR20
2014/0368J-167	SUB A 1.4	167	<0.1		-	-	SA15MAR20

Legend: Take results as guide only. The Nitrogen values were at the limit of detection.

BGallagher

AUSTRALIAN NUCLEAR SCIENCE AND TECHNOLOGY ORGANISATION
New Illawarra Road, Lucas Heights (Locked Bag 2001, Kirrawee DC NSW 2232) T +61 2 9717 3111 F +61 2 9543 5097
www.ansto.gov.au

LIMS Number	Client Identification	Sample No.	Nitrogen Data: N %	Nitrogen Data: $\delta^{15}N_{AIR}$ ‰	Carbon Data: C %	Carbon Data: $\delta^{13}C_{V\text{-}PDB}$ ‰	Sample Comments
2014/0368J-168	SUB A 1.5	168	<0.1		-	-	SA15MAR20
2014/0368J-169	SUB A 1.6	169	<0.1	-0.2 ± 0.6	-	-	SA15MAR20
2014/0368J-170	SUB A 1.7	170	0.1	0.7 ± 0.4	-	-	SA15MAR20
2014/0368J-171	SUB A 1.8	171	0.1	1.2	-	-	SA15MAR20
2014/0368J-172	SUB A 1.9	172	0.1	1.4	-	-	SA15MAR20
2014/0368J-173	SUB A 1.10	173	0.2	2.0	-	-	SA15MAR20
2014/0368J-174	FAR 1.1	174	1.6	1.1	-	-	SA15MAR20
2014/0368J-175	FAR 1.2	175	0.9	0.4	-	-	SA15MAR20
2014/0368J-176	FAR 1.3	176	0.6	1.7	-	-	SA15MAR20
2014/0368J-177	FAR 1.4	177	0.2	2.2	-	-	SA15MAR13
2014/0368J-178	FAR 1.5	178	0.1	1.4	-	-	SA15MAR13
2014/0368J-178(2)	FAR 1.5	178	0.1	1.0	-	-	SA15MAR20
2014/0368J-179	FAR 1.6	179	<0.1	1.6 ± 1.3	-	-	SA15MAR13
2014/0368J-180	FAR 1.7	180	<0.1	2.5 ± 1.1	-	-	SA15MAR13
2014/0368J-181	FAR 1.8	181	<0.1	4.0 ± 1.3	-	-	SA15MAR13
2014/0368J-182	FAR 1.9	182	<0.1	3.0 ± 1.1	-	-	SA15MAR13
2014/0368J-183	FAR 1.10	183	<0.1	2.9 ± 1.0	-	-	SA15MAR13
2014/0368J-184	FAR 1.11	184	<0.1	2.0 ± 0.9	-	-	SA15MAR13
2014/0368J-185	FAR 1.12	185	<0.1	2.1 ± 0.9	-	-	SA15MAR13
2014/0368J-186	FAR 1.13	186	0.1	1.4	-	-	SA15MAR13
2014/0368J-187	FAR 1.14	187	<0.1	1.0 ± 1.0	-	-	SA15MAR13
2014/0368J-188	FAR 1.15	188	<0.1	0.5 ± 1.4	-	-	SA15MAR13
2014/0368J-189	FAR 1.16	189	<0.1	2.5 ± 1.1	-	-	SA15MAR13
2014/0368J-190	FAR 1.17	190	<0.1	2.7 ± 1.0	-	-	SA15MAR13
2014/0368J-191	MAN1.1	191	1.4	1.3	-	-	SA15MAR20
2014/0368J-192	MAN1.2	192	1.0	1.2	-	-	SA15MAR20
2014/0368J-193	MAN1.3	193	0.8	1.1	-	-	SA15MAR20
2014/0368J-194	MAN1.4	194	0.1	2.2	-	-	SA15MAR13
2014/0368J-195	MAN1.5	195	<0.1	0.2 ± 1.2	-	-	SA15MAR13
2014/0368J-196	MAN1.6	196	<0.1	-2.9 ± 1.6	-	-	SA15MAR13
2014/0368J-197	MAN1.7	197	<0.1	-0.1 ± 1.5	-	-	SA15MAR13
2014/0368J-197(2)	MAN1.7	197	<0.1		-	-	SA15MAR20
2014/0368J-198	MAN1.8	198	<0.1		-	-	SA15MAR13
2014/0368J-199	MAN1.9	199	<0.1	1.2 ± 0.9	-	-	SA15MAR13
2014/0368J-200	MAN1.10	200	<0.1	1.6 ± 1.0	-	-	SA15MAR13
2014/0368J-201	MAN1.11	201	0.1	2.1 ± 0.5	-	-	SA15MAR13
2014/0368J-202	MAN1.12	202	0.1	2.3 ± 0.5	-	-	SA15MAR13
2014/0368J-202(2)	MAN1.12	202	0.1	2.1 ± 0.6	-	-	SA15MAR20
2014/0368J-203	MAN1.13	203	0.1	1.2	-	-	SA15MAR13
2014/0368J-204	CAS2.1	204	1.9	-0.03	-	-	SA15MAR20
2014/0368J-205	CAS2.2	205	1.0	0.8	-	-	SA15MAR20
2014/0368J-206	CAS2.3	206	0.6	2.4	-	-	SA15MAR13
2014/0368J-206(2)	CAS2.3	206	0.6	2.2	-	-	SA15MAR20
2014/0368J-207	CAS2.4	207	0.2	1.8	-	-	SA15MAR13
2014/0368J-208	CAS2.5	208	<0.1	-0.7 ± 1.4	-	-	SA15MAR13

Legend: Take results as guide only. The Nitrogen values were at the limit of detection.

BGallagher

LIMS Number	Client Identification	Sample No.	Nitrogen Data: N %	Nitrogen Data: $\delta^{15}N_{AIR}$ ‰	Carbon Data: C %	Carbon Data: $\delta^{13}C_{V-PDB}$ ‰	Sample Comments
2014/0368J-209	CAS2.6	209	<0.1	0.5 ± 1.4	-	-	SA15MAR13
2014/0368J-210	CAS2.7	210	<0.1	1.2 ± 0.7	-	-	SA15MAR13
2014/0368J-211	CAS2.8	211	<0.1	2.0 ± 0.7	-	-	SA15MAR13
2014/0368J-212	SM1.1	212	1.4	2.0	-	-	SA15MAR20
2014/0368J-213	SM1.2	213	1.0	1.5	-	-	SA15MAR20
2014/0368J-214	SM1.3	214	0.3	2.8	-	-	SA15MAR13
2014/0368J-214(2)	SM1.3	214	0.3	2.9	-	-	SA15MAR20
2014/0368J-215	SM1.4	215	<0.1	1.7 ± 1.4	-	-	SA15MAR13
2014/0368J-216	SM1.5	216	<0.1		-	-	SA15MAR13
2014/0368J-217	SM1.6	217	<0.1	1.6 ± 1.4	-	-	SA15MAR13
2014/0368J-218	SM1.7	218	0.1	1.5	-	-	SA15MAR13
2014/0368J-219	SM1.8	219	0.1	1.4	-	-	SA15MAR13
2014/0368J-220	PEAT 1.1	220	1.2	1.4	-	-	SA15MAR20
2014/0368J-221	PEAT 1.2	221	1.5	3.3	-	-	SA15MAR20
2014/0368J-222	PEAT 1.3	222	1.3	2.5	-	-	SA15MAR20
2014/0368J-223	PEAT 1.4	223	1.2	2.8	-	-	SA15MAR20
2014/0368J-224	PEAT 1.5	224	0.9	1.3	-	-	SA15MAR20

Legend: Take results as guide only. The Nitrogen values were at the limit of detection.

The following Standard Reference Materials (SRM) were used for data normalisation in this report

SRM	Lot #	Percentage Nitrogen	$\delta^{15}N$ relative to Air (‰)	Percentage Carbon	$\delta^{13}C$ relative to VPDB (‰)
Sercon SC0419	192702	9.4 ± 0.1	-2.0 ± 0.1	40.3 ± 0.3	-30.3 ± 0.1
USGS-40 L-Glutamic acid	-	9.52	-4.52 ± 0.06	40.8	-26.39 ± 0.04
USGS-41 L-Glutamic acid	-		47.57 ± 0.11		37.63 ± 0.05

BGallagher

AUSTRALIAN NUCLEAR SCIENCE AND TECHNOLOGY ORGANISATION
New Illawarra Road, Lucas Heights (Locked Bag 2001, Kirrawee DC NSW 2232) T +61 2 9717 3111 F +61 2 9543 5097
www.ansto.gov.au

QC CHECKS

RUN NO.	ID	# SAMP	N %	$\delta^{15}N_{V\text{-}PDB}$ ‰	C%	$\delta^{13}C_{V\text{-}PDB}$ ‰
	CERTIFIED VALUES for B2151		**0.62 ± 0.02**	**4.42 ± 0.29**	**9.15 ± 0.12**	**-26.27 ± 0.15**
SA15JAN19	B2151	1	-	-	9.2	-26.4
SA15FEB26	B2151	2	-	-	9.0	-26.5
SA15FEB26	B2151	3	-	-	8.9	-26.6
SA15FEB26	B2151	4	-	-	9.3	-26.6
SA15FEB26	B2151	5	-	-	9.3	-26.4
SA15FEB26	B2151	6	-	-	8.9	-26.6
SA15FEB27	B2151	7	-	-	9.3	-26.6
SA15FEB27	B2151	8	-	-	9.3	-26.6
SA15FEB27	B2151	9	-	-	9.2	-26.6
SA15MAR03	B2151	10	-	-	9.2	-26.5
SA15MAR03	B2151	11	-	-	9.6	-26.6
SA15MAR03	B2151	12	-	-	9.1	-26.6
SA15MAR03	B2151	13	-	-	9.3	-26.6
SA15MAR04(1)	B2151	14	-	-	9.1	-26.6
SA15MAR04(1)	B2151	15	-	-	9.3	-26.5
SA15MAR04(1)	B2151	16	-	-	9.3	-26.6
SA15MAR04(2)	B2151	17	0.6	4.4	-	-
SA15MAR06	B2151	18	0.6	4.7	-	-
SA15MAR06	B2151	19	0.6	4.6	-	-
SA15MAR06	B2151	20	0.6	4.4	-	-
SA15MAR13	B2151	21	0.6	4.7	-	-
SA15MAR13	B2151	22	0.6	4.1	-	-
SA15MAR13	B2151	23	0.6	4.6	-	-
SA15MAR13	B2151	24	0.6	4.6	-	-
SA15MAR20	B2151	25	0.6	4.7	-	-
SA15MAR20	B2151	26	0.6	4.5	-	-
SA15MAR20	B2151	27	0.6	4.6	-	-
		AVERAGE	**0.6**	**4.5**	**9.2**	**-26.5**
		S.D.	**0.01**	**0.2**	**0.2**	**0.1**
		Difference from Actual	**0.01**	**-0.1**	**-0.1**	**0.3**

BGallagher

QC CHECKS

RUN NO.	ID	# SAMP	N %	$\delta^{15}N_{V-PDB}$ ‰	C%	$\delta^{13}C_{V-PDB}$ ‰
	CERTIFIED VALUES forB2178		**0.3 ± 0.02**	**6.3 ± 0.4**	**3.2 ± 0.1**	**-27.7 ± 0.1**
SA15JAN19	B2178	1	-	-	3.2	-28.0
SA15FEB26	B2178	2	-	-	3.3	-27.5
SA15FEB26	B2178	3	-	-	3.2	-27.6
SA15FEB26	B2178	4	-	-	3.2	-27.5
SA15FEB26	B2178	5	-	-	3.2	-27.5
SA15FEB26	B2178	6	-	-	3.2	-27.5
SA15FEB27	B2178	7	-	-	3.2	-27.5
SA15FEB27	B2178	8	-	-	3.2	-27.6
SA15FEB27	B2178	9	-	-	3.3	-27.6
SA15FEB27	B2178	10	-	-	3.2	-27.4
SA15MAR03	B2178	11	-	-	3.2	-27.4
SA15MAR03	B2178	12	-	-	3.2	-27.6
SA15MAR04(1)	B2178	15	-	-	3.2	-27.6
SA15MAR04(1)	B2178	16	-	-	3.1	-27.7
SA15MAR04(1)	B2178	17	-	-	3.2	-27.6
SA15MAR04(2)	B2178	18	0.2	6.5	-	-
SA15MAR04(2)	B2178	19	0.3	6.4	-	-
SA15MAR06	B2178	20	0.2	6.6	-	-
SA15MAR06	B2178	21	0.3	6.3	-	-
SA15MAR13	B2178	22	0.3	6.6	-	-
SA15MAR13	B2178	23	0.3	6.7	-	-
SA15MAR13	B2178	24	0.3	6.6	-	-
SA15MAR13	B2178	25	0.3	6.6	-	-
SA15MAR20	B2178	26	0.3	6.7	-	-
SA15MAR20	B2178	27	0.3	6.7	-	-
SA15MAR20	B2178	28	0.3	6.6	-	-
		AVERAGE	**0.3**	**6.6**	**3.2**	**-27.6**
		S.D.	**0.01**	**0.1**	**0.04**	**0.1**
		Difference from Actual	**0.0**	**-0.3**	**-0.02**	**-0.1**

BGallagher

AUSTRALIAN NUCLEAR SCIENCE AND TECHNOLOGY ORGANISATION
New Illawarra Road, Lucas Heights (Locked Bag 2001, Kirrawee DC NSW 2232) T +61 2 9717 3111 F +61 2 9543 5097
www.ansto.gov.au